# 6G and Beyond: The Future of Wireless Communications Systems

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# 6G and Beyond: The Future of Wireless Communications Systems

**IAN F. AKYILDIZ, (Fellow, IEEE), AHAN KAK, AND SHUAI NIE**

Broadband Wireless Networking Lab, School of Electrical and Computer Engineering,
Georgia Institute of Technology, Atlanta, GA 30332, USA

Corresponding author: Ahan Kak (e-mail: ahan@ece.gatech.edu).

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**ABSTRACT** The next generation of wireless communication networks, or 6G, will fulfill the requirements of a fully connected world and provide ubiquitous wireless connectivity for all. Transformative solutions are expected to drive the surge for accommodating a rapidly growing number of intelligent devices and services. Major technological breakthroughs to achieve connectivity goals within 6G include: (i) a network operating at the THz band with much wider spectrum resources, (ii) intelligent communication environments that enable a wireless propagation environment with active signal transmission and reception, (iii) pervasive artificial intelligence, (iv) large-scale network automation, (v) an all-spectrum reconfigurable front-end for dynamic spectrum access, (vi) ambient backscatter communications for energy savings, (vii) the Internet of Space Things enabled by CubeSats, and (viii) cell-free massive MIMO communication networks. In this roadmap paper, use cases for these enabling techniques as well as recent advancements on related topics are highlighted, and open problems with possible solutions are discussed, followed by a development timeline outlining the worldwide efforts in the realization of 6G. Going beyond 6G, promising early-stage technologies such as the Internet of NanoThings, the Internet of BioNanoThings, and Quantum Communications, which are expected to have a far-reaching impact on wireless communications, have also been discussed at length in this paper.

**INDEX TERMS** 6G, Wireless Communications, Terahertz Band, Intelligent Communication Environments, Pervasive Artificial Intelligence, Network Automation, All-Spectrum Reconfigurable Transceivers, Ambient Backscatter Communications, Cell-free Massive MIMO, Internet of NanoThings, Internet of BioNanoThings, Quantum Communications

## I. INTRODUCTION

WIRELESS communication systems have experienced substantial revolutionary progress over the past couple of years. Various stakeholders, including commercial solutions providers, academic research groups, standards bodies, and end-users, have all greatly benefited from the radical changes led by the most recent 5G developments, which include paradigm-defining techniques such as network softwarization and virtualization, massive MIMO, ultra-densification, and the introduction of new frequency bands. Numerous burgeoning applications and verticals, including virtual and augmented reality (VAR), e-commerce, wireless monetary transactions, machine-to-machine communications, and enhanced mobile broadband, among others, have all demonstrated the vast potential of 5G, which continues to evolve and adapt to a wide variety of emerging use cases.

However, as societal needs continue to evolve, there has been a marked rise in a wide variety of emerging use cases that cannot be served satisfactorily with 5G. For example, the next generation of VAR, i.e., holographic teleportation, requires Tbps-level data rates and microsecond-level latency, which cannot be achieved with even the millimeter wave (mmWave) frequency bands within 5G. Further, increasing industrial automation and the move from Industry 4.0 to the upcoming Industry X.0 paradigm will push connectivity density well beyond the $10^6$ $\mathrm{km}^2$ metric that 5G is designed for, in addition to requiring an overhaul of existing network management practices. Consequently, the research community has gravitated towards addressing the aforementioned major challenges, and we posit that ongoing research in the domains of terahertz band communications, intelligent surfaces and environments, and network automation, for example, may

**TABLE 1.** The evolution from 5G to 6G wireless systems [1].

| Key Performance Indicator | 5G | 6G |
|---|---|---|
| **System Capacity** | | |
| Peak Data Rate (Gbps) | 20 | 1000 |
| Experienced Data Rate (Gbps) | 0.1 | 1 |
| Peak Spectral Efficiency (b/s/Hz) | 30 | 60 |
| Experienced Spectral Efficiency (b/s/Hz) | 0.3 | 3 |
| Maximum Channel Bandwidth (GHz) | 1 | 100 |
| Area Traffic Capacity ($\mathrm{Mbps/m^2}$) | 10 | 1000 |
| Connection Density ($\mathrm{devices/km^2}$) | $10^6$ | $10^7$ |
| **System Latency** | | |
| End-to-end Latency (ms) | 1 | 0.1 |
| Delay Jitter (ms) | NA | $10^{-3}$ |
| **System Management** | | |
| Energy Efficiency (Tb/J) | NA | 1 |
| Reliability (Packet Error Rate) | $10^{-5}$ | $10^{-9}$ |
| Mobility (km/h) | 500 | 1000 |

very well hold the key to the future of wireless.

To this end, an amalgamation of societal needs and technological breakthroughs that serve to enable those needs are the key drivers for a generational leap beyond existing wireless systems. Together, these factors make a strong case for a focused discourse on the next frontier in wireless communications, i.e., 6G systems. We envision that 6G will not only enable a pervasively intelligent, reliable, scalable, and secure terrestrial wireless network, but will also incorporate space communications to form an omnipresent wireless network, in keeping with the need for true wireless ubiquity. This paper details our vision for the future of wireless communications, highlighting emerging use cases and detailing the key enabling technologies that are essential to the realization of 6G.

We begin our discussion on 6G by formally introducing the key performance indicators (KPIs) that are expected to guide the design of 6G systems. While the ITU Telecommunication Standardization Sector (ITU-T) is working on a set of official recommendations for the KPI metrics, the tentative values have appeared in the public domain recently [1]. Table 1 presents these values, and contrasts them against the metrics associated with 5G. In particular, from the table, we note the following classes of KPIs:

- **System Capacity:** This class of KPIs primarily deals with metrics that are associated with system throughput. These include peak data rate, experienced data rate, peak spectral efficiency, experience spectral efficiency, maximum channel bandwidth, area traffic capacity, and connection density. Within this context, the experienced data rate and spectral efficiency metrics refer to the values that should be guaranteed to 95% of all user locations.
- **System Latency:** This class of KPIs includes the end-to-end latency metric, along with delay jitter. We note that jitter is a new KPI for 6G that quantifies the latency variations in the system, and is absent from 5G.
- **System Management:** This class of KPIs primarily deals with metrics related to the management and orchestration of networks such as energy efficiency, reliability, and mobility. Here too we note that while 5G does not specify a target KPI for the energy efficiency metric, 6G introduces a target energy efficiency of 1 Tb/J.

Achieving the KPIs highlighted in Table 1 will require revolutionary breakthroughs across all domains of wireless communications. In particular, we identify the following major thrusts:

- **New Spectrum Usage and Radio Design Paradigms:** While 5G ensured the mainstream adoption of mmWave spectrum, the need for higher data rates and consequently larger channel bandwidths will necessitate the incorporation of terahertz (THz) and sub-THz spectrum within 6G. At the same time, the opening up of new spectrum bands will also require novel radio designs that can simultaneously sense and communicate over the entire EM spectrum.
- **Novel Network Architectures:** The classical cell-based architecture of wireless networks cannot scale to meet the area traffic capacity and connection density requirements put forth by 6G. Instead, 6G will need to incorporate communications infrastructure into the very fabric of the environment.
- **Increasing Intelligence and Automation:** The strict spectral efficiency, reliability, and latency requirements associated with 6G imply that manual configuration of the network will no longer be possible. Rather, network intelligence and automation will occupy centre stage, helping build an increasingly autonomous network.
- **Enhancing Network Coverage Beyond the Terrestrial Domain:** In order to achieve true wireless ubiquity 6G will need to expand beyond terrestrial networks, incorporating both near-Earth as well as deep-space connectivity.

Towards the fulfillment of this grand vision, we note that several enabling solutions have been conceived and are being actively studied. As shown in Fig. 1, these technologies include: (i) a network operating at the THz band with much wider spectrum resources, (ii) intelligent communication environments that enable a wireless propagation environment with active signal transmission and reception, (iii) pervasive artificial intelligence, (iv) large-scale network automation, (v) an all-spectrum reconfigurable front-end for dynamic spectrum access, (vi) ambient backscatter communications for energy savings, (vii) the Internet of Space Things enabled by CubeSats, and (viii) cell-free massive MIMO communication networks. We also make note of three very promising technologies that are expected to shape the future of communications, yet will not be sufficiently mature for 6G. These include: (i) the Internet of NanoThings, (ii) the Internet of BioNanoThings, and (iii) Quantum Communications.

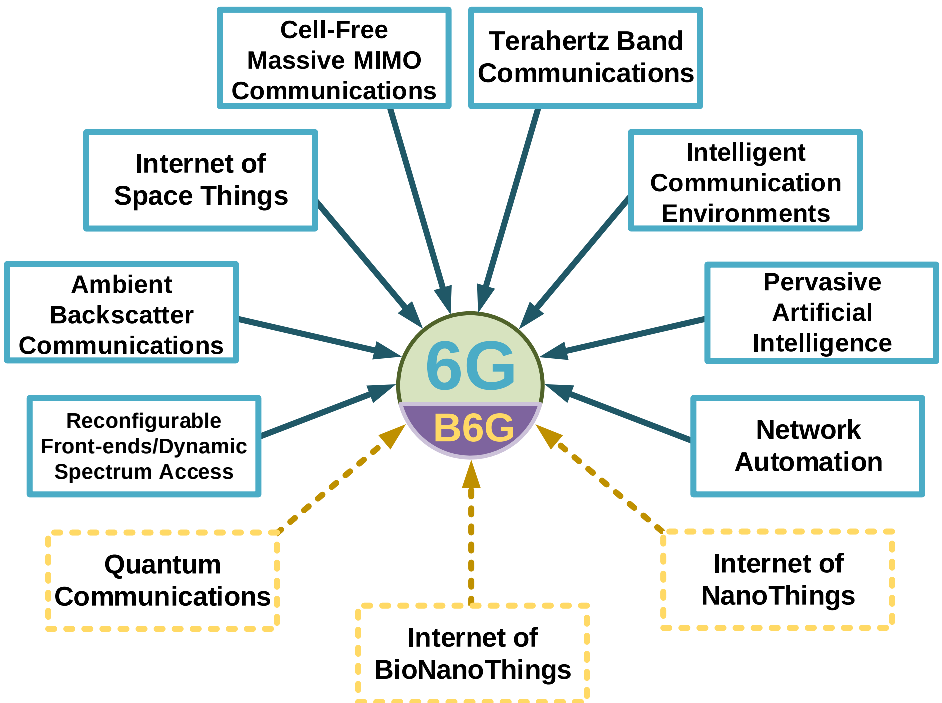



FIGURE 1. The envisioned key enabling technologies for 6G and beyond 6G wireless communications.

Further, in addition to the aforementioned key technologies, holistic security solutions will also be vital to the success of 6G. However, these fall outside the purview of this paper.

As research on 6G wireless systems continues to evolve and break new ground, this paper is intended to equip readers with a targeted insight into the next generation of wireless communications. The rest of this paper is organized as follows. In Section II, we present a wide variety of use cases that will be enabled by 6G. Further, Sections III – VI present details concerning key technologies that are critical to the success of 6G, along with a discussion on the major challenges faced by each. Then, in Section XI, we discuss promising enablers for beyond 6G systems, followed by a timeline for the evolution of 6G in Section XII. Finally, in Section XIII, we conclude this paper.

## II. USE CASES

The lessons learned from the continued evolution of 5G systems will serve as the backdrop for use cases that will be best served by 6G. 5G first introduced the targeted use cases of enhanced mobile broadband (eMBB), ultra-reliable low-latency communication (URLLC), and massive machine type communications (mMTC), intended to serve a wide variety of applications. However, as noted in Section I, there exist a plethora of applications for which the 5G KPIs are not strict enough. As we come to realize the performance trade-offs in terms of throughput, latency, coverage, energy efficiency, and reliability, associated with 5G systems, we can better posit the applications that would benefit the most from 6G.

As shown in Fig. 2, in the following, we present a variety of critical use cases that will be enabled by 6G.

**Multi-sensory Holographic Teleportation:** While virtual reality (VR) and augmented reality (AR) have immensely benefited from eMBB and URLLC introduced as part of 5G, there are many applications such as advanced healthcare including remote diagnosis and surgery, high-resolution sensing for remote exploration, and near-real person video conferencing that cannot be adequately served by a combination of AR and VR. To this end, holographic teleportation has been recognized as the natural successor to AR and VR-based solutions. Unlike existing solutions, holographic teleportation operates in a true three-dimensional space and leverages all five senses– sight, hearing, touch, smell, and taste, to provide a truly immersive experience. At the same time, we note that holographic teleportation requires data rates close to $5$ Tbps and an end-to-end latency of less than $1$ ms [2], both of which are impossible to achieve with 5G systems. Thus, 6G, with its expected Tbps-level throughput and sub-millisecond latencies will play a vital role in building upon the groundwork established by eMBB and URLLC.

**Real-time Remote Healthcare:** The success of remote healthcare solutions primarily depends on both the quality as well as the availability of connectivity [3]. Concerning the former, we note that through its use of key enabling technologies such as THz band communications and network automation solutions, 6G will usher in the highest possible wireless communications quality focusing on very-high throughput augmented with ultra-low latency. Concerning

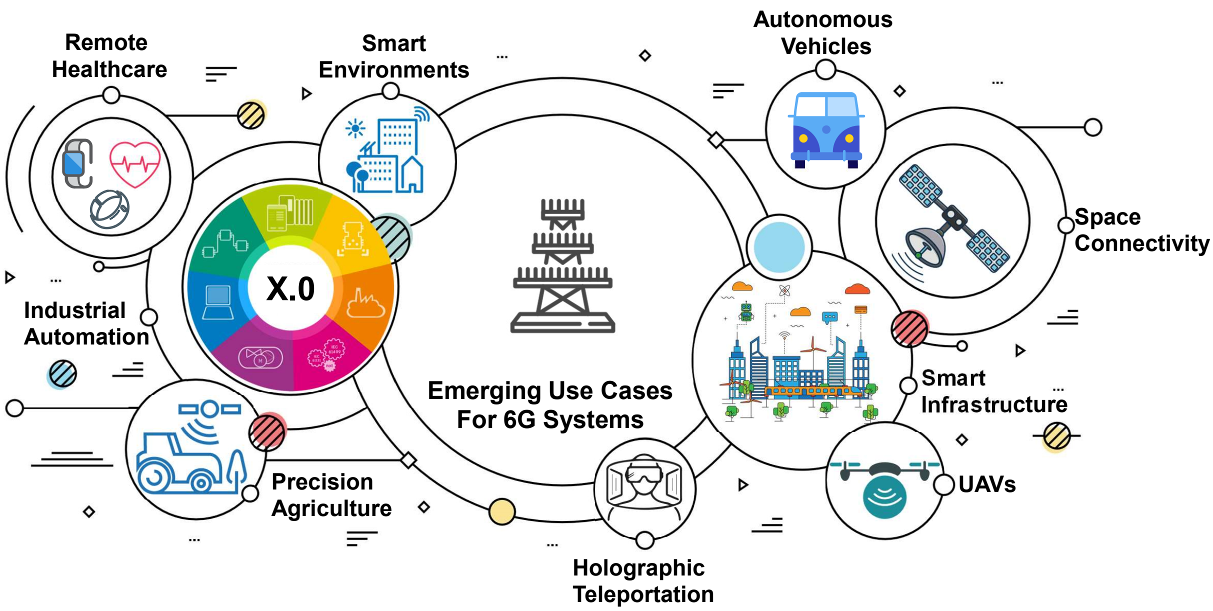



**FIGURE 2.** Use cases best served by 6G systems.

the latter, the Internet of Space Things will play a vital role in providing pervasive connectivity, thus enhancing the availability of rural healthcare solutions. Further, we expect that within the domain of healthcare, 6G will not only serve as a connectivity solution, but will also play a vital role in the diagnosis and treatment of diseases as detailed in Section XI-B.

**Autonomous Cyber-physical Systems:** Autonomous vehicles and UAVs are some of the most promising cyber-physical systems in existence today [4], [5]. The operation of these autonomous systems is characterized by the exchange of large amounts of data between the constituent nodes, i.e., both vehicles and UAVs, relating to high-resolution real-time mapping of the terrain, route optimization, and traffic and safety information. While the resulting large volumes of data must be delivered within strict deadlines in an error-free manner, it also imperative to note that these nodes typically operate at speeds in excess of $100\ \mathrm{km/h}$. Therefore in addition to providing sub-millisecond latency and very high reliability, the connectivity solution that enables autonomous cyber-physical systems must also offer robust operation at very high speeds, which is not possible with existing 5G systems [6].

**Intelligent Industrial Automation:** Over the past few years, Industry 4.0 [7] has been the driving force behind industrial automation based on the concepts of supply chain optimization, autonomous equipment, additive manufacturing, data analytics, and the Internet of Things (IoT). Yet, these concepts are treated as silos working in isolation, limiting the true potential of industrial automation. On the other hand, the upcoming Industry X.0 paradigm [8] seeks to realize synergies between the various nuances of industrial automation through its use of artificial intelligence. Vital to this vision are networked factories that serve as critical sources of big data that helps inform decision making. To this end, the modern industrial floor is expected to require reliable high-throughput connectivity across thousands of devices often with sub-millisecond response times, making it the perfect use case for the next frontier in wireless communications.

**High-performance Precision Agriculture:** Within the broader domain of precision agriculture, soil moisture measurements have been a mainstay in irrigation decisions for decades now. However, real-time measurements and irrigation automation solutions still face challenges stemming from a lack of robust wireless coverage. Going beyond simple automated irrigation solutions, high-performance precision agriculture is largely centered around delivering data-driven insights to address the specific needs of customers, farms, crop, and soil. At the same time, scalable and timely access to such data is a major challenge owing to gaps in rural connectivity. Therefore, we expect that 6G, with its focus on ubiquitous wireless access, will play a major role in enhancing the adoption of technology in agricultural production.

**Space Connectivity:** While near-Earth and deep-space connectivity are still nascent within 5G, there are a wide variety of use cases ranging from reconnaissance and surveillance to navigation and backhauling that would stand to benefit from the pervasive connectivity offered by 6G. More specifically, such applications include freight tracking, terrestrial cellular offloading, environmental monitoring, and long-range UAV coordination to name a few. To this end, the Internet of Space Things as described in Section IX, will serve as the key enabling technology for beyond-Earth connectivity, furthering the reach of 6G systems.

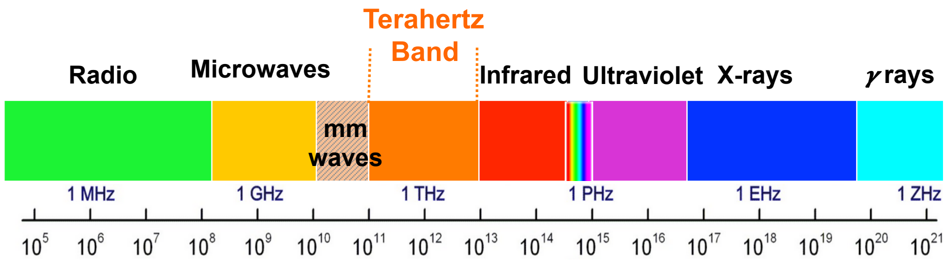



**FIGURE 3.** The THz band offers hundreds of GHz usable spectrum resources for wireless communication links in long, medium, short, indoor, and near-field range.

**Smart Infrastructure and Environments:** The use cases discussed thus far primarily deal with the use of third-party systems that seek to leverage advanced telecommunications infrastructure. Simultaneously, the evolution of such infrastructure itself is an important use case. Going beyond network optimization strategies, there is also a need for exercising control over the propagation of wireless signals. To this end, we note that in 5G and its predecessor systems, the wireless communication environment has always played a passive role. However, with the ever increasing demand for data, as evidenced by the applications presented herein, control over the manner in which electromagnetic waves interact with the indoor and outdoor environment will be critical to the success of 6G. In this direction, we posit that the intelligent communication environments described in Section IV will play a leading role in the ubiquity and pervasiveness of the next generation of wireless systems.

## III. TERAHERTZ BAND COMMUNICATIONS

Recent years have witnessed a dramatic rise in wireless data traffic brought forth by numerous exciting technologies in wireless communications. This exponential growth has been accompanied by the demand for higher data rates and better coverage [9]. Among emerging research and development trends in wireless communications, terahertz band $(0.1 - 10 \text{ THz})$ communications has been envisioned as one of the key enabling technologies for the next decade. Buoyed by the availability of ultra-wide spectrum resources, the THz band can provide terabits per second (Tbps) links for a plethora of applications, ranging from ultra-fast massive data transfer among nearby devices in Terabit Wireless Personal and Local Area Networks to high-definition videoconferencing among mobile devices in small cells.

Recently, the Federal Communications Commission (FCC) has released the frequency bands above 95 GHz for research purposes [10]. While a handful of cellular operators have adopted low millimeter wave frequencies for their 5G services with the intention of achieving a maximum rate of 100 Gbps, the test results thus far leave much to be desired, showing a peak data rate of around 1 Gbps[1]. This gap between the targeted and practically achievable data rates is influenced by multiple factors, including a high complexity in realistic communication channels, imperfections in circuitry design, and interference from other systems operating in adjacent frequency bands, among others. Nevertheless, even though the THz bands have been applied in imaging and object detection, as well as for THz radiation spectroscopy in astronomical research, their use cases in wireless communications are still under investigation. Lying between the mmWave spectrum and infrared light spectrum, as shown in Fig. 3, THz bands, with their abundant spectrum resources, have been previously deemed as a "no-man's land". However, major progress in the domains of transceiver and antenna design has seen THz links become a promising option for realizing indoor communications networks. More recently, there has been significant progress on realizing wireless network on chip (WNoC) using THz bands [11].

[1] https://www.verizon.com/about/our-company/5g/5g-speed-how-fast-is-5g

### A. USE CASES OF THZ BAND COMMUNICATIONS

Different from wireless networks at lower frequencies, THz-band wireless communications has several unconventional application scenarios, owing to the distinct electromagnetic and photonics characteristics of this tremendously high frequency band. In addition to the promised Tbps-level links for cellular systems, THz-band spectrum can also be leveraged for the following scenarios:

- *Local Area Networks:* Several spectrum windows are feasible for short-range links within ten meters, including $625 - 725$ GHz and $780 - 910$ GHz [12]. THz band communications is expected to form the THz-optics bridge to enable seamless transition between fiber-optics and THz-band links with zero latency.
- *Personal Area Networks:* THz band communications can provide "fiber-like" data rate without the need of wires, between multiple devices at a distance of a few meters. Such communication scenarios can be found in indoor offices and multimedia kiosks.
- *Data Center Networks:* Conventional data centers manage and maintain connectivity in wired networks using cables, resulting in high costs in terms of both installation and reconfiguration. On the other hand, THz links provide promising prospects for seamless connectivity

at ultra-high-speeds in fixed networks and adaptability for hardware reconfiguration.

- *Wireless Network on Chip:* As the trend in transceiver hardware development motivates a higher level of integration and miniaturization as well as weight reduction, the THz band links can serve as a promising candidate to establish wireless connections among different modules within the transceiver chassis, in order to replace the wired connections commonly found in existing transceiver hardware products.
- *Nano-networks:* With its wavelength falling into the nanometer ($10^{-9}$ m) range, the THz band can operate better than any other frequencies in nano-networks. Within this context, a nano-network is a set of interconnected nano-devices or nano-machines for information exchange, storage, and computation. A more detailed overview can be found in Section XI-A.
- *Inter-satellite Communications:* Lying largely outside the Earth's atmosphere, inter-satellite links are not constrained by atmospheric attenuation, which makes the THz band a favorable candidate for such communication links. Compared to existing spectrum resources allocated for inter-satellite links, the THz band has a much wider bandwidth which can accommodate more satellites and achieve higher link performance. Unlike the widely used optical links, the THz band does not impose stringent requirements on beam alignment, which can help maintain a high level of link stability as satellites drift out of their orbits.

### B. DEVICES IN THE THZ BAND

The need for higher output power, lower phase noise, and better receiving sensitivity in THz band transceivers has driven advances in corresponding device development. Currently, three main directions are deployed in THz band signal generation: photonics-based, electronic-based, and emerging material-based, respectively.

In the photonics-based approach, many III-V semiconductors, including gallium arsenide (GaAs) and indium phosphide (InP), which provide high electron mobility, are excellent candidates especially for high frequency (i.e., above $100\ \mathrm{GHz}$) applications. Such photonics-based techniques generate time-domain pulses with lengths of femtoseconds ($10^{-15}$ s) and experimental works have demonstrated $50\ \mathrm{Gbps}$ data links in an indoor scenario at $300\ \mathrm{GHz}$ using the uni-traveling-carrier photodiode (UTC-PD) technique [13]. The UTC-PDs and modified UTC-PD structures, an effective photomixing solution which allows wider spectrum tuning and simpler construction compared to laser pulse generators, has pushed the output signal range from $300\ \mathrm{GHz}$ to $2.5\ \mathrm{THz}$, with output powers of $10\ \mu$W at $300\ \mathrm{GHz}$ and $1\ \mu$W at $1\ \mathrm{THz}$ [14]. Additionally, a design based on slot-antenna-integrated UTC-PDs has shown superior performance in generated THz band signal strengths at $350-850\ \mathrm{GHz}$ and $900\ \mathrm{GHz}-1.6\ \mathrm{THz}$, compared to that of the bowtie-antenna integrated UTC-PD [15]. Similar photonics-based THz signal generation at above $1\ \mathrm{THz}$ can be realized using quantum cascade lasers (QCLs) and other solid state lasers [16]. However, the operations of such devices are limited at room temperatures, requiring liquid helium cooling, which affects their deployment in local area networks with space restrictions. Furthermore, photoconductive antennas (PCAs) have been utilized widely for both pulse and continuous-wave signal generation at THz band [17], demonstrating a wide spectrum (up to $4.5\ \mathrm{THz}$) with a remarkable dynamic range of up to $100\ \mathrm{dB}$ [18].

In parallel to the photonics-based approach for THz band device design which down-converts the optical frequencies, the electronic-based THz band signal generation relies on frequency up-conversion using multipliers [19], including frequency doublers and triplers, as well as backward wave oscillators [20]. A recent experiment has demonstrated an all-electronics-based wireless link at $240\ \mathrm{GHz}$ with a throughput of $50\ \mathrm{Gbps}$ and a maximum $29\%$ error vector magnitude using QPSK modulation [21]. The backward wave oscillator, which is a compact design to generate THz band signals based on the mechanism of energy transfer from an electron beam to an electromagnetic wave through a vacuum tube, has been used to generate signals at $300\ \mathrm{GHz}$ with an output power of $1\ \mathrm{W}$ in plasma diagnostics [20].

Among the two commonly used approaches, the photonics-based design benefits from a relatively simpler transceiver architecture based on the photomixing technique, while the electronics-based solution relies on cascaded frequency up-conversion of RF signals, which sets stringent requirements on linear-range operation and potentially limits the terahertz bandwidth. On the other hand, the electronics-based approach is less sensitive to environmental conditions, such as temperature, humidity, among others, which makes it more favorable for outdoor operations, whereas the link reliability from its photonics-based counterpart is affected by scattered particles in the channel, making the THz band link less robust.

Besides these classical approaches for THz band device development, new materials, including graphene, carbon nanotubes, and graphene nanoribbons, are gaining more attention due to their extremely high electron mobility in the order of $8,000-10,000\ \mathrm{cm}^2/(\mathrm{V}\cdot\mathrm{s})$ at room temperature, as compared to $1,400\ \mathrm{cm}^2/(\mathrm{V}\cdot\mathrm{s})$ of silicon, and $8,500\ \mathrm{cm}^2/(\mathrm{V}\cdot\mathrm{s})$ of GaAs, which means that the link throughput can be potentially up to ten times higher than is currently achievable with most semiconductors [22]. The graphene-based devices, offering outstanding mechanical, electrical, and optical properties, have been utilized in the development of power detectors at $600\ \mathrm{GHz}$ [23] and $200\ \mathrm{GHz}$ [24], as well as plasmonic antenna arrays and transceivers [25], [26]. Graphene-based devices have the potential to break new ground in reaching the desired level of performance at much higher frequencies above $1\ \mathrm{THz}$.

### C. PHYSICAL LAYER MODELING AT THE THZ BAND

The realization of wireless communications at THz frequencies requires the development of accurate channel models to capture the impact of both channel peculiarities including the high atmospheric attenuation and molecular absorption rates at various transmission windows, as well as the propagation effects including reflection, scattering, and diffraction, with respect to different materials. Current research has reported several efforts to provide fundamental understanding of such channels. For example, an early work in [27] demonstrates the remarkable capacity the THz band channel can support for short transmission distances. The model provides a detail analysis on the effect of attenuation caused by the molecular absorption and spreading loss, on which the performance of channel throughput is heavily depend. One step further, in order to extend the transmission distance at THz bands, an idea dubbed as the ultra-massive multiple-input multiple-output (UM MIMO) communications, enabled by an element array size of $1024 \times 1024$ with plasmonic nano-antennas, can drastically boost the signal strength by steering and focusing the transmitted beams in both space and frequency [28]. Correspondingly, a UM MIMO channel model has been developed in [29] which takes into account the role of such arrays.

Additionally, a stochastic channel model for indoor THz band communications at 300 GHz has been reported in [30] which characterizes both spatial and temporal domain channel information. More recently, based on the aforementioned applicable scenarios in the THz band, a stochastic channel model for kiosk applications has been reported in [31] which ranges from $200 - 340$ GHz. The main takeaway from current models validated using either measurements or ray-tracing technique is that the direct path between the transmitter and the receiver and the single-bounce reflected paths dominate the received power, while other channel effects, including diffraction and scattering, attenuate power significantly along propagation.

On the basis of the ultra-wideband channel characterization, THz band communications faces a critical and challenging task of synchronization in the receiver design. Existing pulse-based modulation schemes permit the use of low-complexity non-coherent analogue detectors, e.g., energy detector and auto-correlation receiver, which involve the multiplication of the received signal with itself, followed by an integrator. However, a more advanced non-coherent receiver architecture in [32] based on a continuous time moving average symbol detection scheme demonstrates better performance compared to previous detection schemes for pulse-based modulations in terms of the symbol error rate. In addition, robust frequency and timing synchronization for multi-carrier communication in the THz band is desirable to decode multiple incoming signal streams. The work presented in [33] realizes both a low-rate sampling scheme for channels with high SNR values and a maximum likelihood-based algorithm for low SNR channels with satisfying bit-error-rate performance. More recently, a synchronization scheme based on medium access control protocols is reported in [34], which shows good performance in both a macro-scale scenario to overcome the distance limitation at the THz band and a nano-scale scenario for nano-devices to recharge for energy.

Similarly, given the peculiar ultra-wideband nature and frequency selectivity of THz band communications, equalization solutions pose another relevant challenge [35], [36]. In [37], three equalization solutions, including the Tomlinson-Harashima precoding, a waveform with interference management for time-reversal systems, and an iterative algorithm with adaptive soft feedback, are reviewed and compared for an indoor channel. Results show that the iterative algorithm with adaptive soft feedback yields the most promising BER performance [37].

### D. MEDIUM ACCESS CONTROL IN THZ BAND COMMUNICATIONS

On top of physical layer channel models, the medium access control (MAC) schemes in THz band communications should adopt certain spatial and spectral features in order to provide solutions in resolving issues such as the deafness problem and LoS blockage, among others [39], [40]. Different from commonly used MAC solutions in RF systems that utilize omnidirectional antennas, such as carrier sense multiple access with collision avoidance (CSMA/CA), the MAC protocols designed for THz band rely on handshakes between transceivers with highly directional beams. These razor-sharp beams can provide higher power radiation gain and prolong the transmission distance, but when misalignment happens, the deafness problem arises. As such, the deafness avoidance approach is required in MAC scheme design. Existing solutions utilized in IEEE 802.15.3c [41] and others employ a beam-training phase to estimate and steer beams towards destined devices. Recent works also propose methods based on angular division multiplexing [42] and a priori aided channel tracking schemes [43]. The results in such proposed solutions suggest that with good beam alignment strategies the channel throughput can be improved significantly.

Moreover, the MAC protocols can also resolve the issue of LoS blockage where the received power of a user device may undergo deep fading due to the device being held in a manner that blocks the LoS path. Studies have shown that such attenuation by the human body can be as high as 20 dB at 60 GHz and up [44], [45]. To mitigate the blockage problem, researchers have proposed a multi-hop scheme at the mmWave and THz bands to form alternative routes [46], [47]. A careful link-level scheduling and neighbor discovery process is necessary to achieve high throughput while maintaining low interference.

### E. OPEN PROBLEMS IN THZ BAND COMMUNICATIONS

Currently, the fabrication and testing of THz band antenna arrays remains a relevant challenge. Some techniques based on photolithography, electro-beam lithography, among others, are able to produce the front-end with hundreds of plasmonic

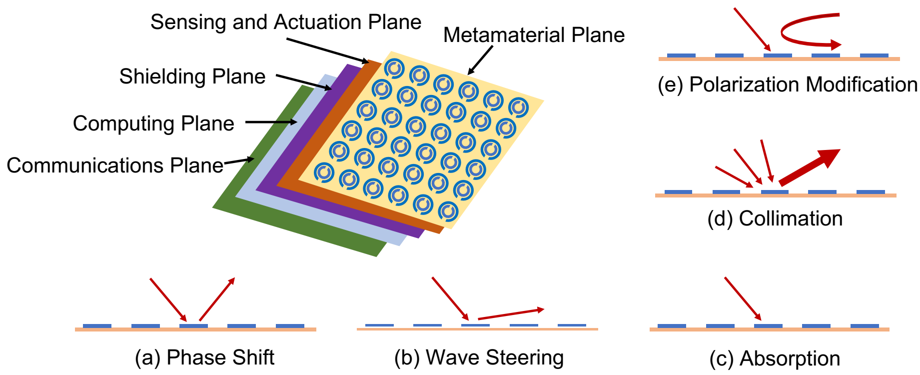



**FIGURE 4.** Conceptual design of a plasmonic reflectarray able to unconventionally manipulate EM waves [38].

antenna elements. The utilization of large antenna arrays can extend the signal coverage by forming array radiation patterns with main lobes of high directivity, thus focusing energy towards desired directions. However, such highly directional beams limit coverage in the angular domain, causing low energy efficiency at the transmitter to serve each user. A recent solution named "THzPrism" has been proposed to form multiple beams with slight frequency shifts towards different directions while maintaining good distance coverage [48]. This design employs true time delays for RF chains before phase-shifters to obtain a prism-like effect, which spreads the original beam into several beams, each with a slight frequency shift with respect to the center frequency.

In parallel to the quest for more novel solutions in antenna design, other remaining challenges reside in the control and signal processing schemes associated with transceiver designs in the THz band. On the one hand, real-time control algorithms are needed. On the other hand, communication protocols for coordination between the transmitter, receiver, and reflectarrays are needed. Among others, in [49], researchers reported a smart reflectarray-assisted mmWave system compatible with IEEE 802.11ad. Besides the design of the reflectarray and a study on deployment strategies, a three-way beam-searching protocol is developed, in which the reflectarray coordinates with the transmitter through a 2.4 GHz control channel in order to discover the best joint transmit and reflect sectors for which the signal at the receiver is maximized. However, this work does not capture the extended functionalities of plasmonic reflectarrays.

## IV. INTELLIGENT COMMUNICATION ENVIRONMENTS

Along with the rapid growth in the number of wireless devices, services, and applications, a corresponding demand for higher speed wireless communications has burgeoned in recent years. Nevertheless, the major challenge at mmWave and THz-band frequencies is the limited communication distance because of the remarkably high path loss inherent to small wavelengths and the limited transmission power of mmWave and THz-band transceivers [50]. Current solutions primarily focus on the advancement of wireless transceiver hardware and software, as well as network optimization strategies. However, the wireless propagation medium has been largely neglected. The wireless communication environments, for both indoor and outdoor scenarios, can be actively utilized in order to become controllable for signal propagation. To control signal propagation in environments is essentially to control how electromagnetic waves interact with scatterers, which include indoor furniture and outdoor buildings as well as other infrastructure. Typically, the controllable behaviors of electromagnetic waves include controlled reflection, absorption, wave collimation, signal waveguiding, and polarization tuning, as illustrated in Fig. 4. The notion of "Intelligent Communication Environments" resides in the control algorithms where deep learning and reinforcement learning are to be exploited to dynamically configure the environments. In the following subsections, we elaborate on these controllable wave behaviors, current research efforts, as well as corresponding open issues.

### A. BASICS OF INTELLIGENT COMMUNICATION ENVIRONMENTS

The intelligent environments can be seen as a three-dimensional structure with several layers, each with different functionalities. Recent research under the EU Research Project "VisorSurf" has demonstrated a structure with five main layers, which are (from top to bottom) the EM behavior layer, the actuation and sensing layer, the shielding layer, the computing layer, and the communication layer, respectively [51]. Specifically, the EM behavior layer is composed of metasurfaces, a two-dimensional representation of metamaterials, and has a tunable impedance to control directions of reflection of the EM waves. Some other works use reflectarray antennas as the top surface [52], [53]. The actuation and sensing layer consists of circuits for phase shifting and sensors for impinging signal sensing. Some options for actuation include PIN diodes with controllable biasing voltage as switches in reflectarray antennas, and complementary metal-oxide semiconductors (CMOS) transistors as well as micro-electro-mechanical (MEMS) switches for metasurfaces. The

shielding layer isolates the upper and lower parts of the layered structure so as to minimize the possible interference. The computing layer serves to control the phase shifts and process sensed impinging waves. To this end, another reported solution makes use of field-programmable gated arrays (FPGAs) to fulfill such functions on metasurfaces [54]. Finally, the communication layer connects all upper layers and serves as the gateway towards the central controller which processes all connection requests, forwards and receives signals, and conducts the aforementioned controlled wave functions.

Compared to existing relays with multiple antennas which are widely deployed in wireless networks, Intelligent Communication Environments offer the following advantages: (i) a higher spatial diversity due to the wide coverage of the intelligent surface with controllable antenna arrays, (ii) a reduced processing time given that the computing and communication layers are directly underneath the surface layer, and (iii) a higher flexibility in network routing when impinging signals come from different directions and the intelligent surfaces are able to collimate waves and reflect them towards desired directions.

### B. FUNCTIONALITIES OF INTELLIGENT ENVIRONMENTS

Bolstered by the layered structure, intelligent surfaces can enable controlled EM wave operations. At micro- and mmWave frequencies, metasurfaces are considered as a good candidate. While at THz bands, graphene-based plasmonic antenna arrays are desirable. In metasurfaces, a meta-atom is the smallest unit, which is a conductor with a size smaller than half the wavelength of the signal. Metasurfaces can thus control the impinging EM waves with a very fine granularity. The meta-atoms are interconnected by a set of miniaturized controllers that connect the switches of the metasurfaces in the computing layer, while a gateway serves as the connectivity unit in the communication layer to provide inter-element and external control. At THz bands, when the metasurfaces do not yield optimal performance, the graphene-based plasmonic antenna arrays serve as a promising alternative.

Compared to metallic antenna arrays, the plasmonic antenna arrays can have much denser element layout and go beyond the conventional $\lambda/2$ sampling of space towards more precise space and frequency beamforming, owing to the physics of plasmonics. In our previous work, we have demonstrated that, graphene can be used to build nano-transceivers and nano-antennas with a maximum dimension of $\lambda/20$ at THz frequencies, allowing them to be densely integrated in very small footprints (1024 elements in less than 1 $\mathrm{mm}^2$), as shown in Fig. 4 [28]. Therefore, by incorporating the graphene-based plasmonic antenna arrays at THz bands and metasurfaces operating at mmWave bands, we can expand the operational spectrum of intelligent environments and utilize them in transmission and reception in a controllable manner.

### C. LAYERED STRUCTURE OF INTELLIGENT COMMUNICATION ENVIRONMENTS

Based on the operating principles of the aforementioned Intelligent Communication Environments, in this subsection, we anatomize the layered structure and detail each layer's functionality.

#### 1) Metamaterial Plane

The metamaterial plane is also the surface plane, as shown in Fig. 4. In designs based on reflectarrays, phase shifts are applied to each element to improve useful signals while canceling interference [52], [55]. The metasurface element proposed in [56] with millimeter-scale dimensions is connected to a PIN diode with a bias voltage to control operation modes, such as altering polarizations.

In general, this layer comprises the supported EM function of the tile as well as its operation principle. In particular, reflectarray employ modifiable phase shifts applied over their surface. In the far field of radiation, reflected rays can be considered co-directional, and their superposition–constructive or destructive–is controlled by the applied phase shifts [57]. Hence, wave scattering or controlled reflecting functions can be attained. Metamaterial tiles, however, operate as surfaces with tunable local impedance [58]. Impinging waves create inductive surface currents over the tile, which can be routed by tuning the local impedance across the tile. Notice that the Huygens Principle dictates that any EM wavefront can be traced back to a current distribution over a surface [59]. As a result, in principle, metamaterials can produce any custom EM function as a response to an impinging wave. Common functions include wave steering, focusing, collimating (i.e., producing a planar wavefront as a response to an impinging wave), polarizing, phase altering, full or partial absorption, frequency selective filtering and even modulation [54], [58].

#### 2) Sensing and Actuation Plane

In order to control the EM waves per actual channel conditions, the programmable surfaces are expected to sense the propagation environment and actuate the upper surface plane accordingly. Such layer contains hardware elements that can be controlled to achieve a phase shift or impedance distribution across a tile.

Commonly, the layer comprises arrays of planar antennas–such as copper patches–and multi-state switches between them. Reflectarray tiles usually employ PIN diodes with controllable biasing voltage as switches [56]. Metamaterials have employed a wider range of choices, both in the shape and geometry of the planar antennas and in the nature of switches. CMOS transistors, PIN diodes, Micro-Electro-Mechanical Switches (MEMS), micro-fluidic switches, magnetic and thermal switches are but a few of the considered options in the literature [60]. Notably, some options–such as micro-fluid switches–are state-preserving in the sense that they require power only to change state but not to maintain it (i.e., contrary to biased PIN diodes). Sensing impinging waves are also necessary for exerting efficient control over

them. While this information can be provided by external systems [61], with dynamic channels and mobile end-users, tiles capable of incorporating sensing capabilities can be immune from the channel aging problem [62]. The sensing can be direct, employing specialized sensors, or indirect, e.g., via deducing some impinging wave attributes from currents or voltages between tile elements.

#### 3) Computing Plane

The computing functionality serves the processing functionality in the controllable surface system. In the metasurface designs in [54] and [56], FPGA-based controllers are connected to the metasurfaces to implement the computing functions. This layer comprises the computing hardware that controls the actuation and sensing elements. Its minimum computing duties include the mapping of local phase or impedance values to corresponding actuator states. Reflectarray tiles commonly implement this layer using FPGAs and shift registers [56].

Metasurfaces, and specifically HyperSurfaces, can alternatively employ standard IoT devices for the same purpose. Moreover, they can optionally include computing hardware elements (ASICs) distributed over the tile meta-atoms [63], [64]. This can enable autonomous and cognitive tiles, where meta-atoms detect the presence and state of one another, and take local actuation decisions to meet a general functionality objective. Nonetheless, these advanced capabilities are not required for programmable wireless environments.

#### 4) Communication Plane

The communication plane passes the signals from the processing layer to corresponding metasurface layer and collects signals from the sensing and actuation plane. In complicated programmable surface systems, communication occurs among planes to realize various EM wave control functions. The command signals normally operate at much lower frequencies compared to the ones emitted from programmable surfaces; such signals prove to be more efficient in tuning the bias voltage of the PIN diodes [54].

This layer comprises the communication stack and connects actuation and sensing layer as well as computing layer with tile-external devices such as controllers. In the simplest case, this layer is implemented within the computing hardware, acting as a gateway to the external world using any common protocol such as the Ethernet. HyperSurface tiles with embedded distributed computing elements additionally require inter-tile communication schemes, to handle the information exchange between smart meta-atoms. Both wired and wireless intra-tile communication is possible [63], [64]. In both cases, the ASIC hardware employs custom and nonstandard protocols.

### D. USE CASES OF INTELLIGENT ENVIRONMENTS

With the utilization of well-coordinated tiles in the Intelligent Environments, the wireless system can be greatly improved in terms of communication efficacy.

#### 1) On Signal Propagation Enhancements

From the perspective of multiple users and moving users, the Intelligent Environments system is envisioned to serve a large number of users with more realistic user patterns, including mobile users and users in a cluster. Additionally, the Intelligent Environments system should ensure physical layer security against jamming and eavesdropping, an increasingly important problem that remains to be solved.

- **Transmission Distance:** For users in the NLoS areas relative to the transmitter, the Intelligent Environments system is expected to extend the transmission distance and reach previously uncovered areas through waveguiding or reflection.
- **Peak Performance:** This includes both received signal strength maximization and delay minimization. Since there can be multiple users in the same environment to be served by the Intelligent Environments system, the peak performance can yield a system-level optimal solution.
- **Interference Mitigation:** Due to the scenario with multiple users, there is inevitably concern of interference. As in the envisioned scheme, each Intelligent Environment unit is dedicated to an individual user, thus the majority of interference will reside in the wireless section of the end-to-end link.
- **Reliability:** The primary efforts in terms of physical layer reliability include using highly directional antennas to nullify jamming, forming exclusion areas, assigning secret keys to legitimate users, and so on. From the perspective of fundamental propagation channels with Intelligent Environments, good reliability is achieved when the eavesdroppers do not have the knowledge of the frequencies where packages are transmitted, or the eavesdroppers are in the same frequency channel but with much higher noise which makes the intercepted data impossible to decode [65]. Therefore, the dedicated links in Intelligent Environments are inherently secure.

#### 2) On the Physical Layer Security

The more frequent data exchange between users and service providers exposes a higher risk of personal and private data leakage. The 6G wireless network should not only inherit existing network secrecy measures, but also provide enhanced physical layer security associated with new enabling techniques. In current 5G networks, highly directional beams are used for mmWave communications in spatial domain to prevent signals from being intercepted. However, a recent study has shown that such pencil-sharp beams are still vulnerable to agile eavesdropping [66]. Other physical layer encryption algorithms, including source coding approaches such as the low-density parity-check (LDPC) code, are demonstrated with optimal performance under specific conditions [67]. Furthermore, existing solutions in the reconfigurable intelligence surface apply reflectarrays, which do not have the capability to effectively distinguish target users from mali-

cious attackers. Hence, a solution based on the Intelligent Environments serves the purpose of identifying unintended recipients, creating null areas, and improving link secrecy rate.

Essentially, the envisioned Intelligent Environments have the capability to sense user locations and exchange such information with a system controller to verify the user's authenticity. Only affirmative users shall be served with signal streams from the sender. On the other hand, connection requests from unauthorized users (i.e., eavesdroppers) will be nullified from attempting to access secure information or even trying to establish links with the sender.

In practice, the Intelligent Environments can be configured to tune the phases of multipath components in the channel, such that those arrived at intended users can be coherently combined with boosted received signal strengths, whereas those intercepted by eavesdroppers will be scrambled or even cancelled due to non-coherent combining [68]. Hence, the good channel secrecy is achieved when such unintended users do not own the knowledge of equalizer to recover the transmitted signals from noise.

### E. OPEN PROBLEMS IN INTELLIGENT ENVIRONMENTS

A number of open problems need to be addressed in order to facilitate the Intelligent Environments in becoming a market-ready solution. These:

- *Trade-off between dimensions and energy consumption:* In terms of real-world applications, the Intelligent Environments are expected to be coated onto surfaces of interior walls and/or ceilings, and building facades, which require dimensions that can both fit specific installation areas and satisfy link requirements. Meanwhile, with more reflectarray elements and RF chains built into the system, the energy consumption will also increase, due to the advanced signal processing circuitry. Therefore, how to achieve an economic solution to balance the overall dimension and energy consumption while serving users to its desired performance is a nontrivial issue.
- *Compatibility with existing solutions:* Current Wi-Fi access points have a mature protocol stack to sense the channel and establish links with users. In order for the Intelligent Environments to assist with improving indoor signal coverage, it needs to be compatible with the IEEE 802.11 series standard. For now this is still under research and serves as a worthy problem for novel solutions.
- *Standardization:* With many candidate approaches being investigated in reflectarrays, metasurfaces, frequency selective surfaces, among others, there has not been a consensus on how to standardize the device architecture, maximum emitted power, and communication protocols. As more ideas evolve, a standardization effort within a work group is necessary towards a solidary framework.

## V. PERVASIVE ARTIFICIAL INTELLIGENCE

In the past few years, the field of artificial intelligence (AI) has witnessed immense growth, leading to its application in a wide variety of fields across both academia and industry. In the realm of communications and signal processing, AI can be readily applied to cognitive radios, remote sensing, computer vision, and network management. More specifically, in the domain of wireless communications, AI and its associated algorithms are also gradually proving their utility in various emerging techniques such as massive MIMO communications which requires efficient channel estimation and symbol detection. Such tasks often do not yield low complexity optimal solutions in complex channels [69], and thus parallel processing inherent in machine learning can be favorably leveraged to enhance computational capacity.

Admittedly, even though current wireless communication networks follow a layered structure, in which each layer primarily serves several functions, applications of AI and relevant algorithms are gradually bridging the gap across layers in a way that can globally optimize the performance in the entire wireless network. However, in order to provide a marked trail to navigate through a plethora of pervasive AI applications, this section is organized based on the existing layers. As shown in Fig. 5, artificial intelligence can be applied to each layer of the wireless network. At the network layer, machine learning (ML) algorithms can be used for traffic clustering to further adapt the network resources to various scenarios [70]. At the physical and MAC layers, deep learning can optimize resource allocation strategies for power distribution, and modulation and coding schemes, among others. Furthermore, machine learning algorithms can also assist with channel estimation and multi-user detection.

### A. AI IN THE PHYSICAL LAYER

Traditionally, physical layer modeling has been model-oriented—a practice in which mathematical models following a certain framework are proposed and optimized under constraints to satisfy a series of pre-determined performance requirements. For example, in order to conduct channel estimation, a channel model is assumed along with other parametric configurations. These model-based solutions usually perform well if the derivation of mathematical models is relatively straightforward or there exists a closed-form solution. The models can then be validated by field measurements or numerical simulations. However, in real-world scenarios, the applicability of such model-based solutions falls short in complicated environments, due to factors such as non-linearity inside systems and uncontrollable interference, among others. On the other hand, another approach, which is based on statistics, or data sets, builds the model through learning from the data. This method is particularly useful when theoretical analysis is intractable or when a closed-form solution is difficult to obtain. For example, in diffusion-based channels commonly found in molecular communication, the channel characteristics depend largely on the environment, making them challenging to model the-

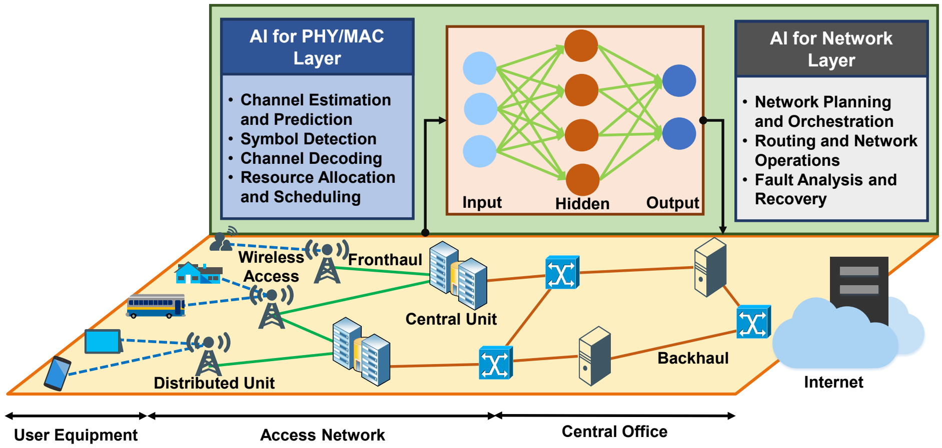



**FIGURE 5.** Applications of artificial intelligence at different layers of wireless systems.

oretically [71]. In such cases, some data is used for training, which can help establish a model, while other data is used for testing in order to validate the model.

To date, artificial intelligence has demonstrated its usefulness in various physical layer techniques. For example, in channel estimation and symbol detection, deep learning approaches reported in [72], [73] have shown that the proposed deep learning-based symbol detection algorithms can provide robust and accurate results with reduced complexity. Furthermore, a deep learning method based on the deep neural network architecture also demonstrates an improved channel estimation accuracy under the effects of non-linearities of power amplifiers, I/Q imbalance, and quantization errors induced by hardware impairments [74]. An autoencoder-based communication system is proposed to reconstruct the transmitted signals from channel impairment based on trained deep neural networks in an end-to-end manner [75]. Furthermore, self-supervised learning is becoming a trend for user localization since it has been demonstrated that relevant methods can significantly reduce the size of labeled dataset for efficient processing [76]

### B. AI IN WIRELESS NETWORKS

In other essential layers of a wireless network, the existence of rich datasets lends itself to the applicability of artificial intelligence-based solutions. In routing protocol design for wireless sensor networks, researchers have successfully utilized reinforcement learning methods to achieve a more energy-efficient routing scheme for underwater sensor networks [77]. In the vehicular industry, autonomous driving has already been studied and become a reality in some cities in Arizona, US[2]. With respect to vehicular communication networks, due to the constant movement of vehicles, a predictive model based on real-time data has superiority over traditional theoretical models in terms of accuracy. Artificial intelligence and its plethora of algorithms can be applied in varied ways in such networks: autoencoders for predicting traffic flow [78], $k$-means clustering for traffic congestion control [79], and $Q$-learning for intelligent resource management [80], among others [81]. In the Internet of Space Things, with our envisioned multi-band communication capabilities in both inter-satellite and ground-to-satellite links, we have proposed a deep neural network-based resource allocation strategy to enable a flexible scheme for CubeSats to stay connected without human intervention from the ground [82].

### C. AI IN NETWORK MANAGEMENT AND ORCHESTRATION

AI, or more specifically ML, has an integral role to play in the management of networks [83]. In fact, Clark et al. introduced the concept of the Knowledge Plane [84] back in 2003, describing it as a pervasive ML-based system within the network that is geared towards providing services and advice to other elements of the network. More recently, with sofware-defined networking (SDN) and network function virtualization (NFV) becoming mainstream, large-scale data acquisition has become easier than ever before, making a strong case for ML-based management and orchestration primitives within 6G, ultimately leading to full network automation as discussed in the next section.

In particular, the domain of network management presents a wide variety of problems that can be broadly categorized into: [83]

- **Supervised Learning:** Supervised learning is typically applied to problems relating to traffic prediction [85] and classification [86], as well as slice resource prediction [87]. While the former primarily involves preemptively determining the network traffic load, as well as determining the applications, protocols and QoS classes the traffic belongs to, for fine-grained traffic engineering, the latter involves predicting the resource

[2]https://www.forbes.com/sites/jonmarkman/2019/11/23/real-autonomous-cars-hit-the-road-in-arizona/#3236f06f32c6

requirements associated with different network slices based on the anticipated traffic load.

- **Reinforcement Learning:** Reinforcement learning typically finds use in problems associated with resource management [88], [89]. For example, the popular virtual network embedding problem wherein the network orchestrator performs optimal placement of virtual network functions onto the underlying physical substrate, is highly amenable to reinforcement learning [90]. Other applications include elastic scaling of network infrastructure [91], failure prevention, and configuration rollback [92].
- **Unsupervised Learning:** While both supervised learning and reinforcement learning have shown significant promise in the network management domain, we note that there exist certain use cases such as those relating to optimizing the end-users' Quality of Experience (QoE) [93] and network security [94] where: (i) labeled data for training is simply not present and (ii) the real-time nature of the application makes it impractical to wait for feedback. In such cases, unsupervised learning can prove to be an indispensable tool. For example, intrusion detection systems based on autoencoders have been shown to outperform supervised learning-based systems [95].

### D. QUANTUM MACHINE LEARNING

Further, we note that in order to effectively handle large amounts of data, machine learning algorithms can be combined with quantum computing for numerous applications [96]. Facilitated by the quantum speedup, the efficiency of a quantum machine learning algorithm can be characterized using measures based on complexity theory. It has been shown in [96] that currently available quantum machine learning approaches, enabled by small-scale quantum computers, have demonstrated noticeable potential in solving classification and regression problems, as compared to classical machine learning algorithms.

### E. OPEN PROBLEMS FOR PERVASIVE AI

While pervasive artificial intelligence in wireless communication networks will undoubtedly bring a paradigm shift towards data-oriented approaches, there are still open problems to be resolved. First, thus far no agreement has ever been reached on which algorithms work the best to solve a generalized problem in wireless networks. Almost all published works claim significant accuracy or reduced complexity with either analytical theories or practical data sets. Additionally, we note the absence of an effective method to draw a fair comparison among all proposed solutions, due to variations in selected data sets, assumptions, evaluation criteria, and so on. However, when it comes to realistic deployments, a careful gleaning process should be performed in order to identify reasonable algorithms without loss of general applicability. Second, the limited availability of quality datasets is detrimental to the testing and validation of proposed classification or regression algorithms. Even though statistical machine learning approaches can analytically prove the upper or lower bound of an empirical risk, the real risk obtained from actual network traffic data can still vary.

## VI. NETWORK AUTOMATION

SDN and NFV have been widely recognized as the major paradigm shifts that occurred with the advent of 5G [97]. In particular, SDN has paved the way for the separation of the data and control planes, while NFV has been instrumental in decoupling the software from the hardware. Consequently, both wired and wireless networks have witnessed significant benefits from the adoption of SDN and NFV, including but not limited to simplified network management and service deployment, availability of advanced traffic engineering solutions and fine-grained network slicing techniques, and reduced CAPEX and OPEX. A major contribution of network softwarization has also been the commoditization of key network components such as switches [98] and base stations [99], [100], allowing for their implementation on COTS hardware. In addition, the large open-source community supporting these projects has played a pivotal role in engaging a wider set of stakeholders than was previously possible.

As networks evolve further, the traditional network operations routine, rooted in manual configuration and static script-based primitives, cannot keep up with the increasing complexity. Instead, we posit that automation will serve as the major driving force behind building upon the improvements brought forth by SDN and NFV. More specifically, network automation is defined as the process of automating the configuration, management, testing, deployment, and operations of physical and virtual devices within a network [101]. Network automation is intended to speed up the delivery of network services while adhering to dynamic and robust service-level agreements (SLAs), and reducing the potential for errors through minimization of manual intervention.

Standardization efforts in this domain have led to the introduction of the Network Data Analytics Function (NWDAF) in the control plane and the Management Data Analytics Service (MDAS) in the management plane, for enhanced data collection and analytics functionalities within 3GPP Releases 15 and 16 [102], [103]. Both these functions form a critical segment of the Service-Based Architecture (SBA) within 5G, highlighting the growing importance of network automation. To this end, we explore three key tenets of network automation in this section– software-defined programmable data planes, automated service decomposition and orchestration, and self-driving networks. While the first two are primarily concerned with automating specific aspects of the network, i.e., the data plane and the network slicing procedure, self-driving networks are the holy grail of network automation, requiring absolutely no manual intervention.

### A. SOFTWARE-DEFINED PROGRAMMABLE DATA PLANES

Being the most popular Southbound API, OpenFlow [104] is synonymous with SDN and has been featured widely in 5G networks. Yet, the stateless match-action abstraction implemented by OpenFlow precludes true data plane programmability since it relies largely on static header field matching. Within the context of this paper, we define data plane programmability as a feature that allows data plane devices, such as switches, to expose their packet-processing logic to the control plane in order for it be completely reconfigured if required. For example, the controller should be seamlessly able to modify the packet parsing and processing pipeline as required, add support for new protocols, and modify existing ones. To this end, P4 [105] is being increasingly recognized as, "the programming language for the data plane". P4 supports a wide variety of hardware ranging from ASICs to commodity CPUs, and allows the controller to specify: (i) a packet parser for extracting header fields, and (ii) a collection of match-action tables that process these headers.

Further, we note that the operation of many applications, depends upon the real-time state of the system, and relying on the controller to update the forwarding state each time introduces a significant latency burden. Consequently, there has been a growing body of research that seeks to develop stateful data planes, wherein some of the stateful packet processing and control tasks are offloaded to the data plane switches [106]–[108]. For example, a stateful data plane device may store some form of packet metadata, using it to process new packets belonging to the same flow. The general packet forwarding rules are still set by the controller, however, the presence of state information provides context for rule selection at the switch-level.

Programmable stateful data planes present a variety of inter-related research challenges. First, there is a need for a generic broad-based definition of state, along with abstractions that expose this state. Second, since packet-level state maintenance will be done by distributed switching devices, there is a need for a state consistency mechanism. A mechanism of this kind could potentially be enforced through the controller, to prevent conflicting forwarding actions. Third, security considerations present another important challenge. If the data plane switches are going to perform actions based on packet metadata, a malicious actor could easily use malformed packets to trigger state transitions for example. In this case, ultra-lightweight mechanisms will be needed to verify packet integrity.

### B. AUTOMATED SERVICE DECOMPOSITION AND ORCHESTRATION

Network slicing allows for the provisioning of differentiated services over the same physical infrastructure [109], and has been a major research focus in the cellular domain [110]–[113]. However, the slice instantiation and deployment process is largely template-driven and requires manual configuration. For example, the current 3GPP network slicing specification [109] is primarily based on the concept of network slice templates (NSTs). An NST explicitly defines the virtual network functions (VNFs) and associated service function chain that comprise a network service. Consequently, such network slicing primitives allow for the deployment of a limited set of network services, i.e., only those services for which a template has already been defined. Clearly, an approach of this kind is not scalable because: (i) it does not provide a mechanism to deal with new kinds of network services, and (ii) as network services increase in complexity, the effort required to create and maintain templates will become an operational burden.

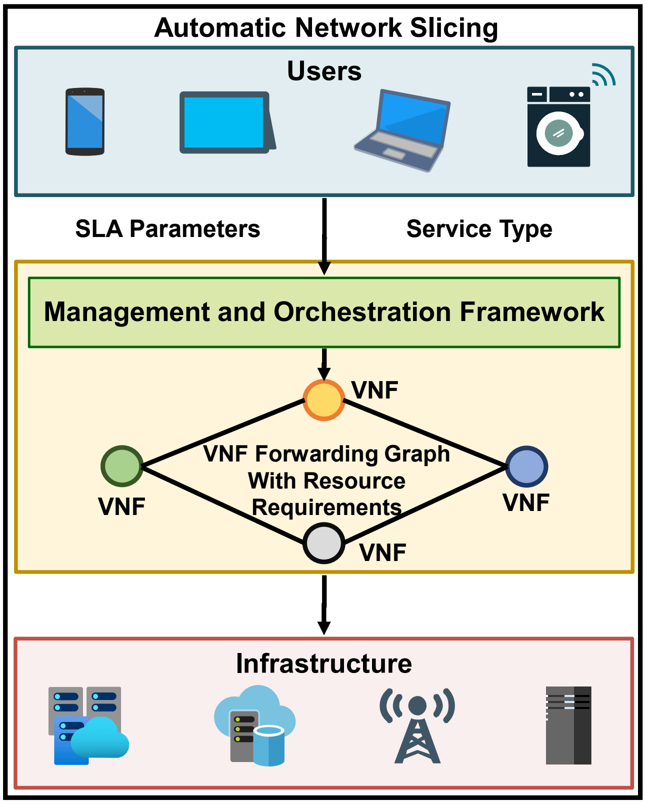



FIGURE 6. Automated network slicing framework.

Going beyond the traditional template-driven model, we propose the concept of automated service decomposition and orchestration for network slice automation, as shown in Fig. 6. To this end, and in line with 3GPP terminology, we identify three major stakeholders– the communication service customers (CSCs), the communication service providers (CSPs), and the virtual infrastructure service providers (VISPs). The CSCs request communications services from CSPs, who instantiate network slices and deploy them over infrastructure owned by VISPs to deliver the requested services. As part of the slice automation workflow, the CSCs provide high-level requirements such as those relating to latency, throughput, reliability, etc., along the lines of the emerging intent-based networking paradigm [114].

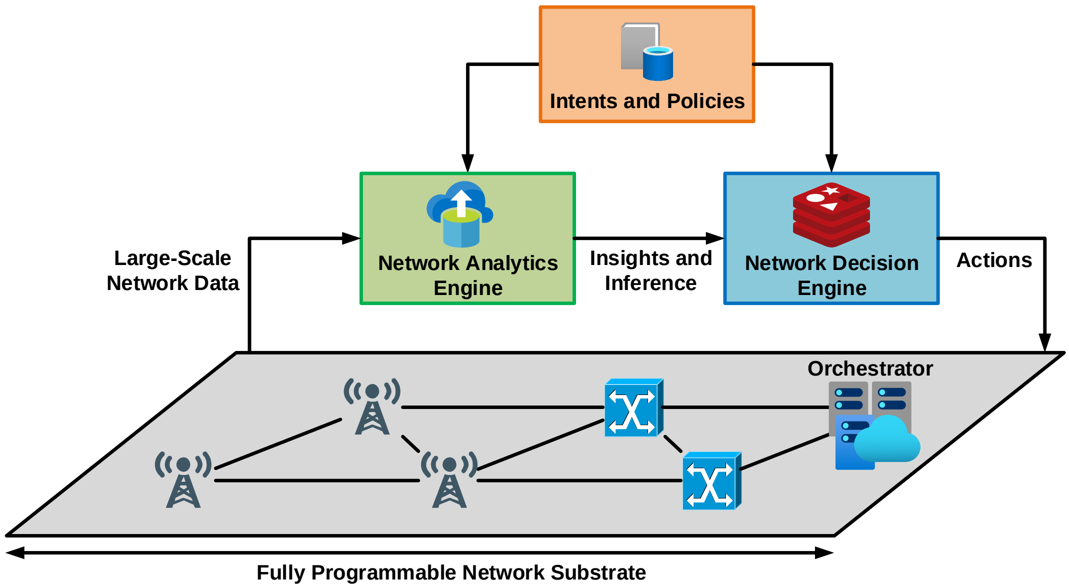



FIGURE 7. High-level architecture for self-driving networks.

Next, the CSC automatically decomposes the request into a constituent VNF-forwarding graph (VNF-FG). It is important to note here that the service to VNF-FG mapping is not a based on a template, but instead makes use of deep learning models to extract service requirements and construct the corresponding VNF-FG. The resulting service-specific VNF-FG also contains the resource requirements for the constituent VNFs, allowing for seamless deployment onto the underlying infrastructure. Once the service has been deployed, continuous monitoring and real-time telemetry are used to ensure operational optimality.

### C. SELF-DRIVING NETWORKS

For decades, the network operator has served as the centerpiece of network operations. However, the increasing complexity of communications networks coupled with the constant state of flux brought forth by an ever-increasing number of connected devices has made the task of real-time network management nearly impossible for human operators. Therefore, there is a strong case for transitioning from operator-driven networks to self-driving networks. More specifically, self-driving networks are expected to allow for elastic utilization of resources, error-free operation, prompt and targeted responses to security incidents, and proactive rather than reactive service handling [115, §2].

Seeking complete automation of network management, a self-driving network is defined as a network where: (i) network measurements are task-driven and tightly integrated with the control of the network, and (ii) large-scale data analytics and machine learning models are used for network control, as opposed to closed-form models of individual protocols [116]. In a nutshell, self-driving networks should be capable of measuring, analyzing, and controlling themselves in an automated manner [117]. At the outset, a self-driving network should take a high-level goal or intent as input. Expanding upon the concept of intents, we note that there are broadly two types of intents– imperative and declarative. While the former describes in explicit detail how a particular procedure should be carried out, the latter just describes the end-goal without specifying how the stated goal should be achieved. For example, “reduce network congestion by shifting incoming traffic originating at ingress node 1 from load balancer 2 to load balancer 3” is an imperative intent since it explicitly defines the steps that network must undertake in order to relieve congestion.

On the other hand, “optimize network operations” is a declarative intent. However, a truly declarative intent of the kind described here would be extremely difficult to implement in the near future. Instead, semi-declarative intents that define more concrete goals would be far more helpful. “Minimize network congestion”, is one example of such an intent since it tasks the network with optimizing its operation by focusing on a specific objective, i.e., minimizing congestion. Based on the intent, the network is expected to determine: (i) the measurements that need to be performed, (ii) the corresponding inferences and learning that is required, and (iii) the actions that must be undertaken in response to the input intent. While a formal representation for self-driving networks is yet to be realized, a high-level architecture has been presented in Fig. 7, highlighting the importance of large-scale data acquisition, real-time analytics and inference, and programmable data planes.

However, the realization of self-driving networks brings forth several research challenges as described next.

- **Accurate Intent Definitions:** As discussed previously, good intent definitions must toe the line between imper-

ative and declarative. If the intent is primarily imperative, it defeats the point of automation. On the other hand, if the intent is purely declarative, the automation procedure becomes unnecessarily complex. Therefore, there is a pressing need for formal guidelines that put forward a clear framework for intent definitions. For example, a framework of this kind could take into account customer expectations in terms of throughput and latency, network-wide resource optimization goals, along with other application-specific functions and services that are required from the network.

- **Automated Real-time Inference:** Machine learning is vital to the automated decision making process in self-driving networks. However, previous work in this domain has largely focused on applying pre-existing learning techniques for network control, which are not well-suited for network data, given its high-volume, distributed nature, and rapid evolution. The major challenge here is the native integration of inference and control algorithms with the network's decision and control fabric. In addition, network design needs to evolve to improve the quality of data that is input to the designed control algorithms [116]. Within the domain of self-driving networks, it is widely accepted that quality of data (QoD) is a pre-requisite for quality of service (QoS) [116].
- **In-band Telemetry:** Research into in-band telemetry (INT) has been largely driven by the need for high quality network monitoring data, without introducing additional overhead. The INT approach makes use of programmable data planes to encapsulate additional metadata within the data packets themselves [118]. Examples of such metadata include switch processing times, buffer occupancy levels, and even specific policy rules. As the packet traverses the network, they keep accumulating additional metadata, which can be extracted as desired, thus providing highly-detailed accurate sets of network data. To this end, there is a need to quantify the impact of INT on network performance [119]. In particular, metrics such as the relationship between the amount of metadata and packet size, the additional processing burden introduced, and the accuracy of the measurements obtained are all important parameters that merit careful consideration.

## VII. 6G RADIO: RECONFIGURABLE TRANSCEIVER FRONT-ENDS

The massive increase in the number of wirelessly interconnected devices, combined with the ever-growing demand for higher wireless data rates, is leading to an overcrowded electromagnetic (EM) spectrum. To overcome the spectrum scarcity problem and increase the capacity of wireless networks, communication at frequencies beyond RF (i.e., from the mmWave to the THz bands) is required. To meet the data-rate, reliability, and scalability requirements from RF to THz, transformative solutions are needed which include the design, implementation, and optimization of frequency-agile, ultra-broadband reconfigurable systems. A system of this kind is able to simultaneously sense and communicate over the full EM spectrum (1GHz to 10 THz), and serves as a major contributor towards the infrastructure needed for the next generation of wireless communications. To realize this vision, pioneering contributions are required in terms of: (i) new devices that surpass the limits of CMOS technology by leveraging the state-of-the-art in materials science and nanoscale physics, (ii) heterogeneous integration of such devices which is compatible with the electrical, thermal, and EMI requirements for reconfigurability and manufacturing scalability, and (iii) novel all-spectrum dynamic sensing and communication algorithms, which maximize the achievable network capacity.

The primary goal for 6G radio is to establish dynamic all-spectrum sensing and communication from RF to THz bands, therefore, transforming the way in which wireless devices sense, access, and share the EM spectrum. To achieve such a goal, key steps include: (i) intelligent all-spectrum sensing solutions, (ii) transceiver hardware design and implementation, and (iii) spectral and energy efficiency optimization as well as resource management. It is worth noting that currently reported works are fulfilling part of this grand goal by achieving dynamic spectrum sensing or multi-band communications over several frequency bands. It is our hope to motivate advanced solutions to realize all-spectrum communications through this section.

### A. DYNAMIC ALL-SPECTRUM SENSING AND ACCESS

In recent times, a concentrated research effort at the physical and link layers has driven exciting progress at RF frequencies for individual cognitive radios (CRs). For example, a recently awarded research project by the Research and Innovation Program in the United Kingdom named "6G Mitola Radio" aims to establish self-regulating societies for wireless communications with fairness and high efficiency [3]. This research will facilitate seamless convergence across heterogeneous wireless networks with intelligent decisions made by radios to maximize the quality of experience for end-users.

One step further, a major challenge is to develop innovative spectrum sensing and sensing-informed communication and network optimization techniques for dynamic access to all-spectral resources. Within this context, the targeted breakthrough would be the development of wireless network-aware state inference using all-spectrum cartography for cognition over the swath of frequencies from RF to the THz bands, along with cartography-constrained algorithms for the physical and cross-layer control protocols. Artificial intelligence and associated learning algorithms should be investigated for dynamic spectrum sharing with a minimum cost in interference. The techniques developed should wholly exploit the capabilities of the hybrid front-ends, which in-

[3]https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/T015985/1

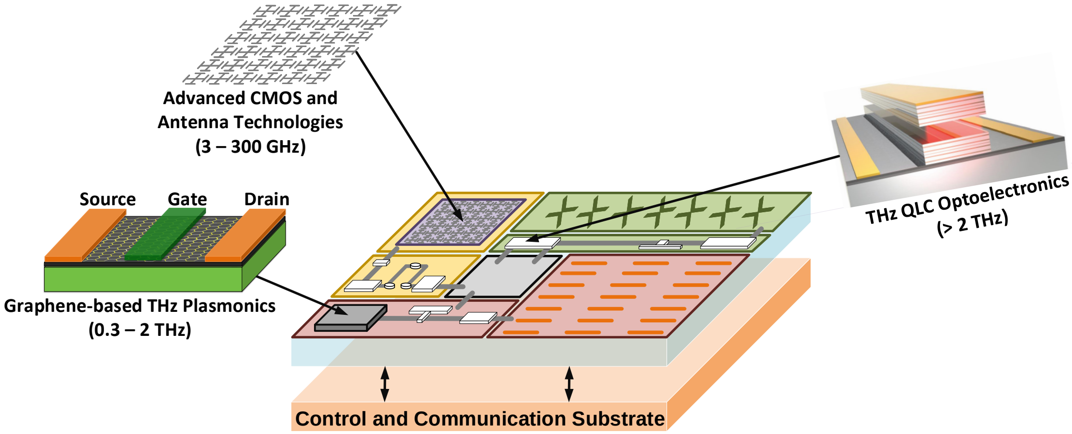



**FIGURE 8.** Conceptual design of a hybrid front-end for dynamic all-spectrum sensing and communication in 6G.

clude a multi-band transceiver design and solutions for resource management.

### B. MULTI-BAND TRANSCEIVER DESIGN

The optimal selection of materials and devices needed to enable all-spectrum communications is vital to the success of any multi-band transceiver design. Existing solutions mostly rely on CMOS for multi-band operations, but such an approach only works well in narrowbands. Moreover, solutions based on software-defined radios (SDRs) have high energy consumption and carbon footprint, consuming several Watts in operation [120], [121]. Instead, novel approaches based on metamaterials, MEMS switches, and even nanoelectromechanical systems (NEMS) switches should be sought to implement hybrid front-ends (Fig. 8), which are able to simultaneously sense the EM spectrum, identify the best available band, and communicate over it, at frequencies anywhere from $1\text{GHz}$ to $10\text{THz}$. Furthermore, fast-evolving deep learning algorithms serve as an efficient solution for identifying available spectrum, tuning channels, and adjusting RF power levels.

To realize this vision, new techniques in materials and devices, integration and packaging, and spectrum sensing and communication are necessary. At the RF and microwave frequency bands, a combination of low-risk mature CMOS technology, with less-mature, potentially transformative technologies, including quantum cascade lasers (QCLs) and new plasmonic technologies based on graphene and other 2D materials will be able to provide optimal tunabilities as well as a high quality factor (i.e., the Q-factor). The heterogeneous integration of discrete devices into a fully functional front-end will require innovation to satisfy material compatibility, EMI shielding, thermal dissipation, and scalability requirements. On the other hand, metamaterial and nano-materials will be deployed at sub-THz and THz bands, based on recent advances in nano-tubes and graphene, as well as other single-atom-thin semiconductors. Space-time-frequency coding in metasurfaces will also allow programmable and fine-tunable radio access at mmWaves. Optimal control of the front-ends requires innovative all-spectrum sensing, utilization and sharing techniques, new waveform and hierarchical modulation designs to maximize the capacity and distance in ultra-broadband systems, and scalable networking solutions which are able to support the envisioned node density in future cyber-physical systems.

The combination of several cutting-edge techniques can help maximize: (i) spectrum utilization (toward all-spectrum utilization), (ii) data-rates (toward terabit-per-second links) and, (iii) network user capacity (billions of interconnected wireless devices). The proposed technology will enable a plethora of applications in the consumer, military, industrial and medical fields, including transformative networking architectures designed to meet the scalability demands in future cyber-physical systems.

### C. RECONFIGURABLE FRONT-END SCHEME

Accompanying the dynamic all-spectrum sensing and multi-band operation, agile front-ends should also be equipped with reconfigurability. In terms of hardware design, the plasmonic reflectarrays can be deployed in the 3D environment, with a size ranging from $1\ \text{mm}^2$ to $100\ \text{mm}^2$ depending on the operating frequency (mmWave/THz-band). Owing to the sub-wavelength size of their elements, the plasmonic reflectarrays are able to reflect signals in non-conventional ways, which include controlled reflections in non-specular directions as well as reflections with polarization conversion [122]. In order to adapt to dynamic frequency operation, achieve various levels of directivity, and allocate multiple beams, the aperture of plasmonic reflectarray antenna can be controlled mechanically through folding, splitting, or combining in a 3D space. Existing prior art using origami antennas works well in systems using a single metal antenna, as reported in [123], [124]. However, to achieve reconfigurable continuous aperture antenna arrays, plasmonic reflectarrays offer a higher degree of freedom with the compactness of unit element distribution.

On the other hand, electronically-controlled reconfigurable antenna arrays are envisioned by leveraging the tunability of plasmonic antennas. In particular, one of the relevant properties of graphene-based plasmonic nano-antennas is the possibility to change their resonant frequency by utilizing a small voltage to modify their Fermi energy [125]. The possibility to tune an antenna (or group of antennas) at different frequencies without any mechanical modification (as opposed to other multi-band antenna arrays that utilize MEMS or NEMS to create origami type structures [126]) enables beamforming not only across space but also across frequencies.

### D. OPEN PROBLEMS

The biggest hurdle to be overcome lies in the implementation of an integrated ultra-broadband hybrid front-end that is capable of sensing and communication from the RF to the THz bands, over a target distance of a few hundred meters. Meeting this multidisciplinary challenge requires us to" (i) close the THz gap by developing new device technologies, (ii) design and integrate re-programmable circuitry, interconnects and antennas that can support all-spectrum operation, (iii) develop new material integration and packaging techniques to satisfy the electrical, thermal and EMI requirements of disparate bands, and, (iv) develop scalable all-spectrum communication using the front-ends.

## VIII. AMBIENT BACKSCATTER COMMUNICATIONS

In the realm of IoT, sensors are expected to function in various environments with long-lasting battery life. Solutions such as radio frequency identification (RFID) utilize the backscatter technique to modulate and reflect RF signals instead of generating them, which can achieve a significant degree of energy saving. However, existing modulated backscatter solutions have stringent requirements in terms of the proximity between the backscatter transmitter and the RF source, due to the attenuation of the signal over long distances. Besides, the modulated backscatter transmitters are passive, which means that they cannot transmit data without requests initiated by backscatter receivers [127]. Furthermore, the issue of self-interference may arise when the backscatter receiver and RF sources are co-located. Hence, in order to achieve better energy efficiency with a higher degree of flexibility and scalability, new solutions are required in the 6G IoT network.

Currently, with more small cells being deployed in outdoor and more access points in indoor environments, the RF signals are covering a wide range of surroundings, and can be considered as a resource to be utilized by secondary radio links without requiring extra power. The system that employs such a technique is called an “ambient backscatter communication system”. In an ambient backscatter communication system, transmitters can harvest the surrounding and continuous electromagnetic waves radiated by TV towers, base stations, as well as access points, use simple circuits for modulation, and reflect them towards receivers. There is no need for dedicated spectrum bands for such ambient backscatter transceivers to operate, nor complex electronic components (e.g., analog-to-digital converters) to process signals.

### A. OPERATION PRINCIPLES OF BACKSCATTER COMMUNICATIONS

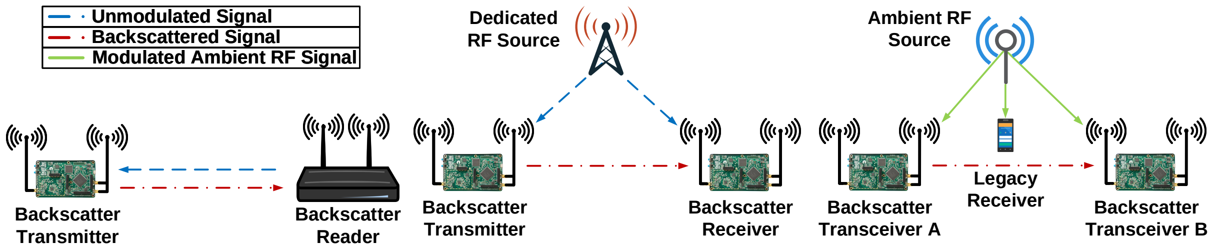
In general, as the name suggests, backscatter communication systems reflect signals impinged on a backscatter transmitter in the direction of the signals' origin, and since it is not a perfect specular reflection, the signals are scattered within a certain angular range of the environment. A backscatter communication receiver within the range can thus pick up the signals. In particular, backscatter communications have three variations in terms of architecture, which are monostatic, bistatic, and ambient backscatter communications, respectively. Here we briefly explain the first two types and then focus on the last one.

As the most commonly adopted backscatter communication approach with widely-used RFID applications, monostatic backscatter communication systems have the simplest setup, which consists of a backscatter transmitter and a reader. The reader has both an RF signal source and a backscatter receiver embedded with a switch to change the operation mode. Once the receiver sends out a request, the RF source activates the backscatter transmitter, which then modulates and reflects the EM waves impinged on it back to the receiver, as shown in Fig. 9. Such a design is mainly used for short-range RFID applications [127]. Nonetheless, two drawbacks of the monostatic backscatter communication architecture are (i) the reader cannot perform full duplex communication due to the switch mechanism, and (ii) the signals experience round-trip path loss being sent from the reader to the transmitter and then reflected back to the reader.

On the contrary, in the bistatic backscatter communication architecture, the RF source and receiver are separated, as shown in Fig. 9, which provides higher flexibility in the spatial domain. With multiple RF sources and backscatter transmitters well placed, the serving range can be remarkably extended compared to the monostatic backscatter scenario. Despite this improvement, it is more costly for bistatic backscatter communication systems to operate in real networks, since they require RF sources and transmitters to be well-placed so as to achieve desired performance, and most of the times this condition can be difficult to satisfy, especially in a sophisticated network environment, such as an indoor office or dense urban scenarios.

### B. MECHANISM OF AMBIENT BACKSCATTER COMMUNICATIONS

Different from the monostatic backscatter device where the transmitting and receiving components are separately located and the RF source is co-located with the receiver, devices of ambient backscatter communication systems consist of both the transmitter and receiver. Additionally, distinct from bistatic backscatter communications, ambient backscatter




(a) Monostatic backscatter communications. (b) Bistatic backscatter communications. (c) Ambient backscatter communications.

**FIGURE 9.** Illustration of backscatter communication systems.

communications do not require dedicated RF sources to provide exclusive services, which can reduce infrastructure and maintenance expenditure significantly. Therefore, the ambient backscatter communications provide the most energy-efficient solution for sensors in the IoT network in 6G. Specifically, in one proof-of-concept study for utilizing the always-on radio signals for ambient backscatter communications reported in [128], TV signals serve as the RF source, which can be amplitude and sometimes frequency-division modulated.

In the ambient backscatter transmitter design, a simple switch consisting of a transistor and connected to the antenna can be used to modulate the impedance of the antenna: a mismatch of impedance indicates a reflection mode of the impinging signals, whereas a matched impedance allows for the signal being absorbed by the antenna [128]. The power consumption of such 1-bit modulation of signals is minimal. At the receiver side, by demodulating the received sequence of "1" and "0", signals can be successfully recovered. However, it is worth noting that since the reflected signals from the ambient environment already contain encoded information from the RF source system (e.g., cellular or TV networks), the receiver design should take into consideration how to extract the backscattered signals from the mixture.

Besides the simplicity in transceiver implementation, ambient backscatter communications are not restricted to a single-band operation. In fact, the ambient backscatter transceivers can operate in the wide range of super high frequency (SHF) bands, covering Bluetooth, Wi-Fi, and other bands [127].

### C. OPEN PROBLEMS IN AMBIENT BACKSCATTER COMMUNICATIONS

- *Spectral and Energy Efficiency:* Currently, the research and development of ambient backscatter communications is still in its infancy. As mentioned before, careful planning of backscatter devices is crucial for achieving good performance. Due to the randomness in IoT device deployment, current solutions fall behind in terms of the targeted spectral efficiency. Specifically, the randomly-located IoT devices should utilize ambient backscatter links to achieve a satisfying throughput while maintaining an extended transmission distance. Additionally, even though individual backscatter communication devices demonstrate good energy performance, an IoT network comprising hundreds or even thousands of such devices might still require optimization of energy efficiency on a system level.
- *Protocol Design:* Existing ambient backscatter communication systems are mostly used for dedicated application-specific purposes, and thus lack good compatibility with other wireless communication systems. Standardization and protocol design are necessary to formalize the key operation and management aspects of ambient backscatter communications, such as packet size, routing protocols, among others.

## IX. INTERNET OF SPACE THINGS WITH CUBESATS

The Internet of Space Things (IoST) is a spatial expansion of the basis of the Internet of Things, which primarily focuses on terrestrial use cases. For future communication networks, this expansion is necessary for the following reasons: (i) the IoT relies heavily on existing infrastructure and hence lacks flexibility as well as scalability, (ii) global coverage is impossible using traditional IoT solutions, especially in remote areas including the North and South Poles, due to the imbalance of construction expenditure and service revenue, and (iii) limited heterogeneity and spectrum resources in the IoT network.

To this end, IoST is envisioned as a ubiquitous cyber-physical system spanning ground, air, and space, with applications in monitoring and reconnaissance, in-space backhauling, and holistic data integration [129]. More specifically, as shown in Fig. 10, IoST consists of the IoST Hub, Customer Premises, and on-Earth sensing devices which form the ground segment, and the CubeSats and near-Earth sensing devices that form the space segment. The ground-to-satellite links (GSLs) connect the IoST Hubs with CubeSats to exchange requests and data, and the inter-satellite links (ISLs) relay information to neighboring CubeSats, in both the same orbit as well as adjacent orbits. Since the space segment forms a vital component of the system, recent research has largely focused on the deployment of small satellites, or CubeSats [131], to fulfill such advancements to achieve the IoST and leave no man behind [129].

CubeSats are a set of miniaturized satellites with sizes

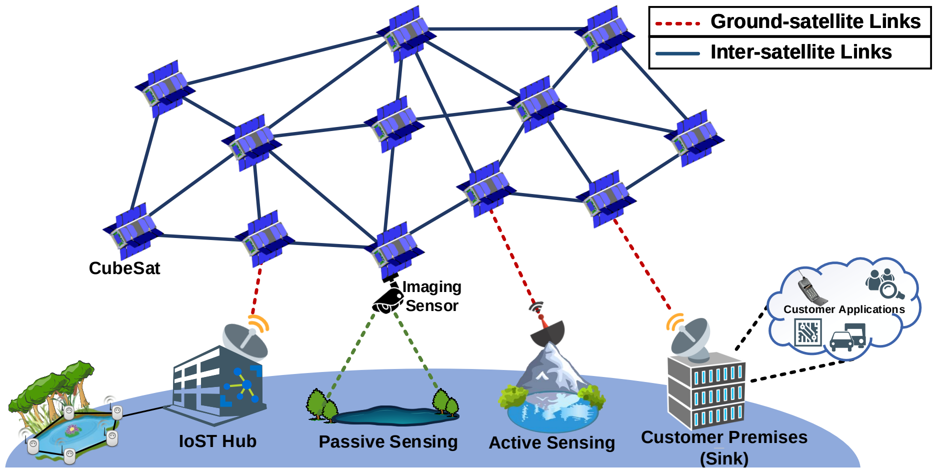



FIGURE 10. Illustration of the IoST [129].

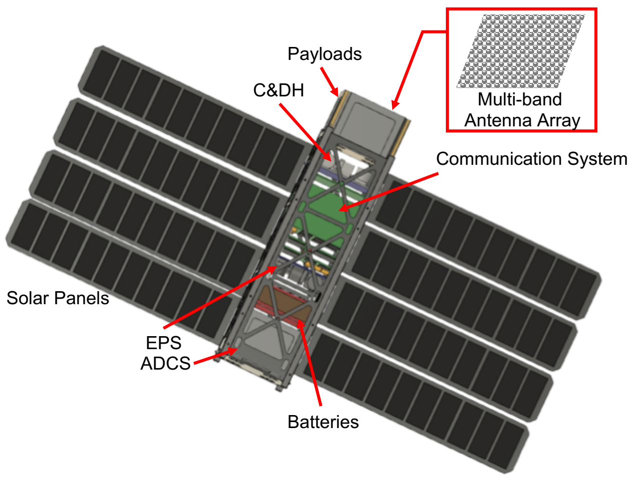



FIGURE 11. Conceptual design of a next-generation CubeSat [130].

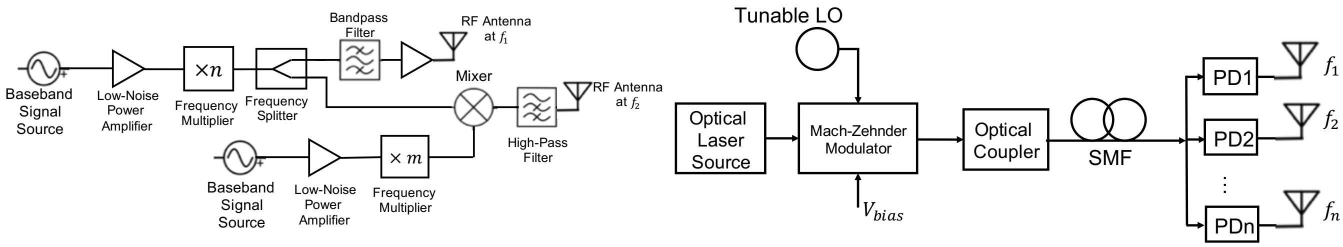
ranging from 1U to 6U (a "U" is $10 \times 10 \times 10$ cm$^3$). Currently, CubeSats are being deployed for a variety of applications including Earth sensing [132], positioning, and IoT and machine-to-machine communications. Compared to traditional LEO satellites, CubeSats present a number of advantages relating to (i) lower costs and shorter development cycles and (ii) higher flexibility and scalability [130]. Normally the development cycles range from three to seven years for traditional LEO and GEO satellites and the costs are extremely high. Also, since the payloads are pre-determined in the LEO and GEO satellites from the period of development until deployment, it is difficult to reconfigure any component in the middle of the process. However, CubeSats' development can be done in a remarkably shorter time using commercial off-the-shelf (COTS) components with much lower costs. This also guarantees that CubeSats are easily reconfigurable.

To this end, we have recently proposed a new next-generation CubeSat hardware concept as shown in Fig. 11 [130]. The proposed CubeSat design includes an all-new communications subsystem for seamless operation in a wide variety of frequency bands. More specifically, the novelty of our design is characterized by the presence of multi-band transceivers and antennas that are able to support wireless communications at microwave, mmWave, and THz frequencies as detailed in the following section.

### *A. MULTI-BAND COMMUNICATIONS SUBSYSTEM*

The primary motivation for a multi-band communications subsystem comes from the fact that existing CubeSats have limited communications capabilities, largely relying on spectrum that lies between the L- (1–2 GHz) and Ka- (26.5–40 GHz) bands. There are two major drawbacks associated with this approach. First, the traditional frequency bands are becoming increasingly prone to congestion [133]. Second, the Tbps-level throughput required by IoST cannot be met by existing frequency bands. To overcome the spectrum scarcity and capacity limitations in current satellite networks, we have proposed the use of multiple frequency bands from RF to THz, in IoST [130]. The use of such frequencies has been made possible by advances in high-frequency device development [134], [135]. More specifically, as part of the multi-band communications subsystem, we have developed both multi-frequency transceivers as well as antenna systems, as described next.

As shown in Fig. 12, in our proposed multi-band transceiver, we use two complementary approaches, namely, an electronic frequency up-converting chain and an optical frequency down-converting chain, to generate signals at different frequencies. With regard to the electronics-based approach, the primary idea is to use frequency splitters in order to extract the intermediate frequencies for outputs. For example, as shown in Fig. 12, the signal at frequency $f_1$ is considered as the intermediate output when producing signals at a higher frequency $f_2$.




(a) Electronics-based approach.

(b) Photonics-based approach.

**FIGURE 12.** The proposed all-spectrum signal front-end designs [130].

On the other hand, the photonics-based approach involves the down-conversion of optical signals. As shown in Fig. 12, multi-band signals are generated by heterodyning two input signals with a Mach-Zehnder modulator. The resulting RF signal has a frequency equal to the difference between the two inputs. The generated signal, along with the two input signals, serves as the final output. Distinct from the commonly used up-conversion and down-conversion techniques where intermediate frequency products are abandoned, our approach harvests them and utilizes them as part of the multi-band communication system. These multi-band frequencies can be assigned to the GSLs and ISLs dynamically to accommodate various service requirements. To this end, within IoST, the GSLs make use of the more robust microwave and mmWave frequencies, while high-capacity THz links form the ISLs.

In addition to multi-band transceivers, CubeSats in the IoST are also equipped with multi-frequency antenna systems. In particular, as discussed in Section III, the use of THz links allows for very large antenna arrays that serve as the basis for massive MIMO and UM MIMO communication schemes. More specifically, we note that there exist multiple options when it comes to the design of multi-band antenna arrays. The first approach involves the use of NEMS, MEMS, and origami structures to create physically re-configurable antennas, wherein the size of the radiating elements can be changed physically with a view to adjust their resonant frequency. On the other hand, the second approach proposes the use of materials such as graphene to create electronically tunable nano-antenna arrays [136], [137]. In this case, the resonant frequency can be controlled by modulating the graphene Fermi energy or chemical potential. This allows for tuning of the antenna to resonate at different frequencies without physically changing its size, as is the case with the MEMS-based approach.

### B. SYSTEM CONSTELLATION DESIGN

Within the context of IoST, an ideal constellation design is crucial to achieve true global coverage and satisfactory link performance. However, conventional LEO constellations are typically characterized by the presence of fewer than a hundred satellites, for example, the CubeSat-based IoT system, Astrocast, has a maximum of 64 satellites [138]. At the outset, the coverage and connectivity offered by such systems leaves much to be desired. Motivated by the need for improved coverage, reliable connectivity, and increased redundancy, mega-constellations of several hundred satellites have gained significant traction over the past year [139]. Mega-constellations provide several advantages over traditional constellations including but not limited to increased coverage density, improved connectivity, and higher redundancy.

More specifically, constellation design typically involves solving for several inter-related parameters such as: (i) the apogee and perigee radii, (ii) the orbital eccentricity, (iii) the number of CubeSats per orbital plane, (iv) the number of orbital planes, and (v) the initial longitude of the ascending node, argument of perigee, and true anomaly of the CubeSats. While a fairly challenging problem in itself, the presence of an extremely large number of satellites further serves to complicate the system design. Consequently, the existing state-of-the-art constellation design frameworks are largely geared towards the design of systems with a few dozen satellites at best. To this end, we have proposed a highly-scalable and customizable constellation design framework that takes into consideration both coverage and connectivity parameters [140]. Through the use of novel metrics such as spherical Voronoi tessellation based coverage characterization and ISL feasibility-based connectivity parameters, we are able to demonstrate that the resulting IoST constellation achieves a performance level that is similar to existing state-of-the-art mega-constellations such as Starlink, while requiring only a quarter of the satellites.

### C. NETWORK MANAGEMENT

IoST encompasses a vast infrastructure spanning both the Earth as well as space. A complex network of this kind has much to benefit from fine-grained real-time control that is well suited for tackling the peculiarities of the space environment, namely temporal topological variation and long delays. Going beyond the traditional bent pipe nature of satellite communications systems, IoST makes extensive use of software-defined networking (SDN) and network function virtualization (NFV) to significantly improve network

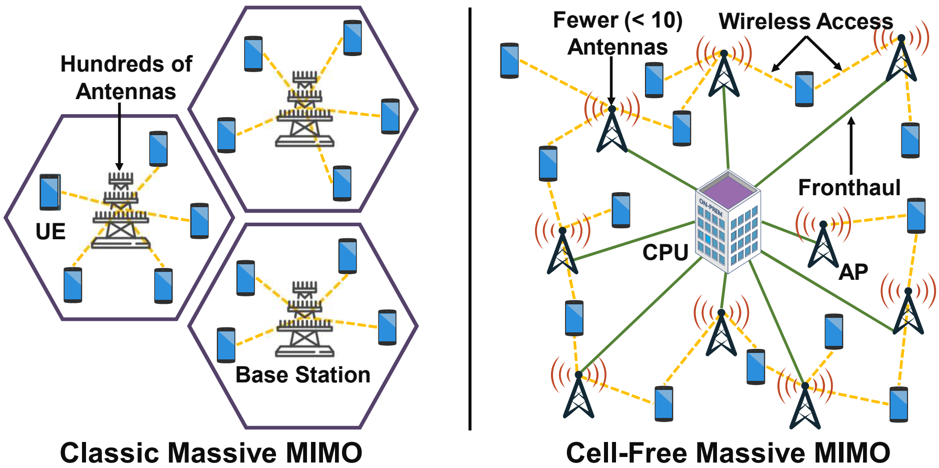



**FIGURE 13.** Cell-free massive MIMO in comparison with classic massive MIMO.

resource utilization, simplify network management, and reduce operating costs [129]. In a manner similar to the infrastructure-as-a-service (IaaS) paradigm, IoST intends to deliver CubeSats-as-a-service.

More specifically with the domain of network management, IoST introduces the novel concepts of virtual CSI (vCSI) for joint optimal physical-link layer resource allocation, and stateful segment routing (SSR) for overcoming challenges associated with the high latency space segment. In particular, concerning the latter, IoST extends the traditional SDN paradigm by including support for state-based packet forwarding that takes into account the topological configuration of the network at any given instance of time, while the use of segment routing helps in the minimization of control traffic. Further, IoST also employs predictive algorithms to preemptively detect GSL outage events, which when coupled with gateway diversity result in the realization of proactive handovers that minimize handover interruption time. In addition, IoST proposes the use of containzeration [141] in CubeSats for achieving lightweight hardware virtualization without significant overhead.Going forward, we note that the aforementioned techniques will play a vital role in the realization of pervasive cyber-physical systems of this kind.

## X. CELL-FREE MASSIVE MIMO COMMUNICATIONS

In 5G wireless networks, massive MIMO communications have been tested and deployed at base stations (BSs) which are equipped with more than one hundred antenna elements to increase the antenna array gain and take advantage of the diversity gain. A related concept is network MIMO, which, instead of packing more than one hundred antenna elements at a single BS, forms a coordinated framework consisting of multiple BSs, each with multiple antennas. A coordination scheme of this kind can achieve spatial diversity by allowing a single user to be served by more than one BS at the same time, overcoming the disadvantage of bad channel conditions if only one BS is connected to the user, and eliminates inter-cell interference [142]. However, a detailed comparative study has shown that massive MIMO communication schemes outperform network MIMO with respect to end-user received signal strength and overall costs in configuration [143].

Going one step further, in order to effectively eliminate inter-cell interference caused by users located at cell boundaries, based on the ideas of distributed MIMO communications and coordinated multi-point (CoMP) communications, researchers have proposed the concept of cell-free massive MIMO communication. In a scheme of this kind, the originally densely-packed antenna array set with a few hundred elements at the BS is distributed in a fairly large area in the form of smaller sets with fewer than 10 antenna elements, while still serving a similar number of users in the same area [144]. As shown in Fig. 13, the main difference between cell-free and classic massive MIMO communication systems is that instead of associating each user terminal to a cell with a BS equipped with a large number of antenna elements, it relaxes the restriction of cell boundaries, which can significantly reduce or even eliminate the inter-cell interference. Without cell boundaries, all BSs, or a subset of BSs, can serve users simultaneously in a coordinated manner. In coordination, the cell-free massive MIMO BSs can share with each other the data to be sent to users through fronthaul links.

It has been shown that the BSs can use their local channel state information (CSI) to achieve satisfactory performance and avoid the excessive computation complexity associated with sharing global channel conditions with all BSs [145]. The local CSI can be estimated in the uplink channel in a time division duplex (TDD) mode. Then, precoding is performed based on the obtained channel information at the BSs, before data transmission in the downlink channel. The transmit power and precoding vector can be determined based on the geographic proximity of users to the BSs.

Compared to the small-cell architecture in 5G, which con-

sists of non-cooperative base stations that can serve up to $100$ users per cell with a smaller area (e.g., up to a $200$-meter cell radius) and reduced power in signal transmission (e.g., up to $10$ Watts), a cell-free massive MIMO communication system achieves significantly better performance, since each user can be served by a dedicated access point. A reported study in [146] has demonstrated that the cell-free massive MIMO scheme improves $95\%$-likely per-user throughput by five times and by ten times under correlated shadow fading, with respect to the small-cell solution. More specifically, the same study has reported that when considering realistic channel conditions, including pilot contamination and imperfect CSI, cell-free massive MIMO systems demonstrate much higher throughput compared to small cells and, more importantly, are more robust to impacts such as shadow fading, non-coherence interference, as well as noise [146].

However, we also note the following challenges: (i) due to the issue of aliasing, channel estimation for signals received by different antenna elements is more complicated compared to that of ordinary massive MIMO communications, (ii) with the significantly increased synthesized aperture size, the range of near-field propagation grows larger, hence requiring a different channel model for characterizing the large- and small-scale channel parameters.

### A. CHANNEL CHARACTERISTICS OF CELL-FREE MASSIVE MIMO COMMUNICATION SYSTEMS

It has been theoretically proven that as the number of antenna elements approaches infinity, adversarial channel effects, including inter-cell interference, small-scale fading, and others, will disappear [147]. In cell-free massive MIMO communications, such effects will also have a negligible impact on propagation channels. Specifically, channels under a coordinated scheme of this kind will satisfy the conditions of favorable propagation [148]. Favorable propagation conditions imply that the channel vectors between the BSs and UEs are orthogonal, so that the sum-rate can be maximized. This characteristic is most prominent in classic massive MIMO communications [149]. In cell-free massive MIMO systems, it has been shown that favorable propagation conditions can be achieved given that the number of APs is fairly large (with an approximate density of $1000/\mathrm{km}^2$).

### B. OPEN PROBLEMS IN CELL-FREE MASSIVE MIMO COMMUNICATIONS

As the domain of cell-free massive MIMO communications is relatively new, there are several open problems that merit further investigation. Among them, we posit that coordination and optimization challenges will critically affect the entire system performance and future deployments.

- **User Scheduling:** Extensive studies have been conducted on channel characterization and capacity analysis. However, the prior art does not take into consideration scenarios involving networks with a large number of users to serve. In such cases, there might be an upper bound for the number of APs to serve a user in order to maintain an acceptable-level of average throughput. Current works assume that all users will be served simultaneously under the same frequency resource block. However, when the number of users grows to a threshold where they can no longer be served at the same time, a scheduling scheme that achieves fairness should be considered.
- **Location Optimization of APs:** Existing works in cellular networks draw heavily upon stochastic geometry where cell structures follow 2D Voronoi tessellation and geographically separated BSs that serve cell-edge users under the coordinated multipoint (CoMP) scheme to improve overall system efficiency and overcome inter-cell interference through scheduling [150], [151]. It is therefore crucial to optimize the placement of BSs under practical link-level constraints such as signal-to-interference ratio as well as success probability for individual links to enhance network fairness [152]. In cell-free massive MIMO, since no cell boundaries are assumed, system-level performance pertaining to locations of APs, random scatterers, as well as users should be thoroughly investigated and optimized.

## XI. TECHNOLOGIES FOR BEYOND 6G

Thus far, we have presented in great detail the key drivers that are expected to play an integral role in the next-generation of wireless networks. However, in addition to these, we also note the presence of several promising early-stage technologies that are tipped to revolutionize how we perceive data communications in the near future. To this end, in this section, we discuss three such promising paradigms, namely, the Internet of NanoThings, Internet of BioNanoThings, and quantum communications.

### A. INTERNET OF NANOTHINGS

In addition to the need for more spectrum resources to accommodate a plethora of wireless devices and services, a variety of transformative wireless communications scenarios are also envisioned to become a reality in the 6G realm. In particular, with the advent of wireless ubiquity, we note the existence of situations where electromagnetic waves do not yield acceptable performance or lack reachability due to hardware limitations, such as in high-salinity water or intravascular channels where the transmission range can be extremely short. In the aforementioned application scenarios for THz band communications, as the frequencies of operation increase, the wavelengths of signals fall into the nanometer range (i.e., $10^{-9}$ to $10^{-7}$ meter in size), thereby motivating studies on nano-network communications [153], [154]. Different from those operating at lower frequencies in the microwave range, the devices and transceivers used in the Internet of NanoThings (IoNT) are in the scale of nanometers, and thus behave differently from classical wireless communication systems.

Given the much smaller size, each nano-thing consumes much less energy and is envisioned to be self-powered (e.g.,

via vibrational energy harvesting using piezoelectric nanogenerators [155]). Besides conducting signal transmission tasks, the nano-things can also perform basic processing and data storage, as well as enabling new nano-sensing capabilities with higher sensitivity. Current advancements in nanotechnologies provide several promising candidate materials with various dimensions for creating such nanomachines, including a thin strip of graphene named graphene nanoribbons, graphene in form of a three-dimensional (3D) roll named carbon nanotubes, and graphene spheres.

Communications in the paradigm of nano-networks mainly falls under two categories, which are (i) encoded signal bits being carried with molecules, which follows a diffusion-based mechanism elaborated in Section XI-B1 and (ii) plasmonic radiation on metamaterial-based antennas including graphene and carbon nano-tubes operating in the THz band. These plasmonic antennas [125], [156]–[158] leverage the physics of Surface Plasmon Polariton (SPP) waves, i.e., confined EM waves resulting from the global oscillations of electrons at the interface of a conductor material and a dielectric material, to efficiently radiate at the target resonant frequency while being much smaller than the corresponding wavelength. This property allows them to be integrated in very dense arrays, beyond traditional antenna arrays. The ratio between the free-space wavelength $\lambda$ and the SPP wavelength $\lambda_{\text{SPP}}$ is known as the plasmonic confinement factor, and depends on the plasmonic material properties and the operation frequency. The higher the confinement factor, the smaller the antennas and the higher the density in which they can be integrated.

#### 1) Essential Components in the IoNT

Similar to traditional communication networks, several key components are seen in IoNT [159]:

- **Nano-nodes** are the basic functional units in the nano-network, and have sizes ranging from 1 to 100 nanometers, and can form a cluster to forward and receive signals. A typical nano-node with full transceiving capability contains the following elements: a nano-antenna and a plasmonic nano-tranceiver based on graphene advancements to propagate SPP waves, a nano-processer with operating frequency close to 1 THz, nano-actuators, nano-sensors which can sense external force, gas molecules, and biological objects such as antigens and antibodies, a nano-memory which allows storage of a bit signal in a single atom, a nano-battery , and an energy nano-harvester which transfers energy to power other elements [160]. Limited by the computation capabilities and battery life, the signals are mostly pulse-based for the easiness of detection and transmission.
- **Nano-routers** control the behavioral patterns of the nano-nodes, aggregate information, and determine the optimal paths for signals to be forwarded. The nano-routers are equipped with higher energy and computational resources. When a specific query is created from the command center, nano-routers need to select the optimal routes that can reach the nano-nodes to collect their data and report back. Due to the limited transmission range, a pulse-based signaling is preferred to assess the reachable range of nano-nodes in order to minimize outage probability and establish the desired routes.
- **Gateways** serve as the remote controller of the IoNT and connect over the internet to service providers. The gateways can be common smart devices such as smartphones and tablets, among others. In order to achieve a manageable network with hundred or even thousands of nano-nodes dissipated in sophisticated communication environments, gateways should devise a holistic approach in disseminating commands and queries, coordinating between possible collisions, and processing noisy data, which requires a drastically different network framework than the conventional network architecture. Based on the arbitrary pattern of the nano-nodes, potential solutions can be found with the assistance of artificial intelligence, which does not require pre-established model for prediction.

It is worth noting that major device technology in the IoNT is still under design and development. Although a few types of individual components, such as nano-sensors, have been made available, it is estimated that a major paradigm shift for the IoNT is expected in the second half of the 2020s.

#### 2) Applications of the IoNT

In the realm of IoNT, applications can be primarily found in body area networks and short-distance local environments. Three typical application scenarios are described as follows (also illustrated in Fig. 14):

- **Nano-Cameras:** The nano-cameras are based on nano-photosensing and nanotechnology to sense, combine, and process light signals before transforming them into electric signals. This system includes nano-photodectors, nano-lens, nano-batteries, and nano-memories in order to achieve fine-resolution imaging and signal processing. The nano-cameras can be applied to a wide range of scenarios including but not limited to intravascular imaging and fracture detection in oil pipelines [159].
- **On-Chip Networks:** With microchips getting more compact in dimension while the complexity of functionality grows, on-chip signal transmission has become significantly more challenging. Currently, issues relating to CPU scalability and efficient memory synchronization have driven research trends towards wireless network-on-chip (WNoC) solutions, which can replace wired connections on conventional chips and take advantage of short-range communication in the nano-network at THz-band frequencies [161].
- **Nano-robots for IoNT:** The nano-robots in nano-networks can be deployed in environments such as

nuclear power plants and oil pipelines which might be hazardous for humans to perform tasks but require high precision and do not allow massive drilling or digging over existing infrastructure. Under these circumstances, nano-robots can be dissipated to sense and collect data relating to chemical concentration, and fluid speed, among others. By forming ad-hoc networks, the nano-robots can aggregate and forward data packets to gateways in the IoNT. Nano-robots are also being widely researched in biomedical engineering fields. To this end, Section XI-B will delve into nano-robots for healthcare applications.

#### 3) Open Problems in the IoNT

The significant size shrinkage brings three major challenges. The first one is power efficiency optimization. Even though nano-devices consume power at the level of microwatts when transmitting femtosecond long pulses, in order to cover an area of a few square meters such as an office or a meeting room, the energy consumption factors in as a major constraint in maintaining a satisfying overall network performance. New designs on duty cycles for nano-transceivers should be proposed and evaluated, as well as new clustering algorithms in order to group nano-transceivers in close proximity for adaptive operations.

The second open issue is interference control, which has been extensively studied in classic wireless network scenarios. However, the conventional approaches cannot be directly applied to the IoNT realm, due to the higher density of nano-transceivers in space and pulse-based signal transmission schemes. Self-interference becomes the most prominent issue for nano-transceivers when full duplex mode is deployed and hence requires novel scheduling algorithms to mitigate this adversarial effect. Additionally, new modulation and coding schemes should be developed to fit the need of nano-devices on spectral and power efficiency while maintaining a low probability of crosstalk among links.

The third challenge resides in the network protocols. Since the IoNT will foreseeably function in a manner that is drastically different from the IoT due to differences in channel conditions, limited scale of operation, as well as miniaturized devices, the protocol stack design still remains an open field for exploration.

### B. INTERNET OF BIONANOTHINGS FOR HEALTH APPLICATIONS

Highly relevant to IoNT, with its unique characteristics and applications, is the concept of the Internet of BioNanoThings (IoBNT). First introduced in 2015, the IoBNT has garnered significant traction in its efforts to synergistically combine telecommunications with healthcare solutions [162]. The IoBNT is a network of molecules which can communicate with each other. The types of molecular communications include artificial cells which act as gateways to translate between different molecule types, or a bio-cyber interface

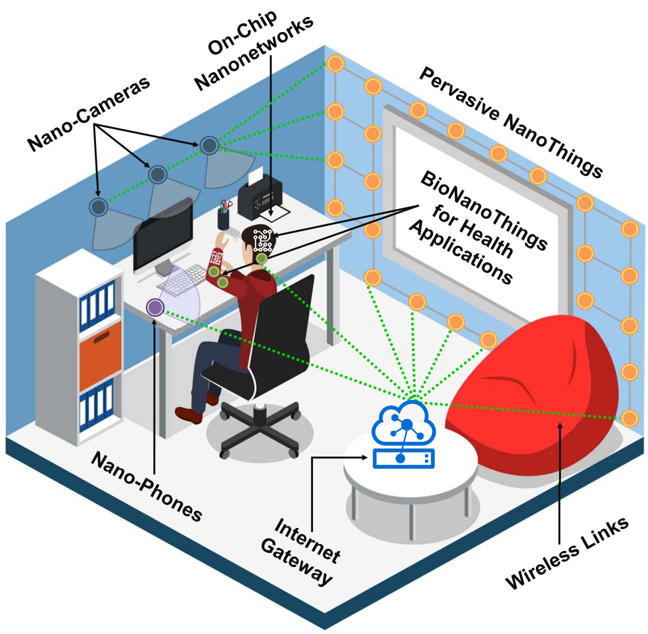



FIGURE 14. Application scenarios of molecular communications in IoNT and IoBNT.

which can convert molecular signals to electrical ones and transmit to external devices for further processing [163].

In applications relating to human healthcare, the IoBNT harbors many unique challenges and opportunities. First, the interdisciplinary research on both communications and data analytics can greatly facilitate the modeling of biological processes, including cancer cell formations and Alzheimer's disease, and further design effective control measures for such diseases. Second, even though expressions of genetic codes at the cell- and organ-level can vary remarkably, in a manner analogous to various types of data applications in wireless networks, communication models can be developed and exploited to conceive a generally applicable health information framework. Third, the holistic network architecture envisioned in the IoBNT will integrate components at heterogeneous levels including within cells and among tissues, organs, as well as systems, before eventually connecting to the outside Internet for physicians to perform metric evaluations and propose treatment plans accordingly. However, healthcare solutions that are to be realized in such complicated biological and molecular environments should be built upon a solid understanding of the physics behind molecular communication and advanced statistical analysis tools in order to unveil the principles behind the seemingly random molecular movement.

#### 1) Essential Communication Models in IoBNT

Different from classic wireless communication channels based on the propagation of electromagnetic waves, molecular communication (MC) channels rely on the mechanism of molecular movement to transmit information. The main difference between an MC channel and the classical wireless

channel is that the transmission medium presents different forms, such as fluids of several chemical compositions in blood vessels, plasma membranes of neurons, and so on. Based on the motion of molecules in such diverse mediums, end-to-end channel models have been developed to characterize the capacity, noise, and interference in various communication scenarios [164]–[166]. Particularly, in the diffusion-based MC model, information is encoded in various forms, for example, based on different concentration intensities and distinct release times of molecules.

The nano-device acting as a transmitter emits such encoded molecules to the wireless molecular channel. At the receiver side, another nano-device decodes the signals based on the quantified received intensities or times of arrival, given that the channel remains stationary for the duration of transmission. In such transmissions, some molecules will get dispersed in the channel and will not be received by the target nano-devices, they are hence treated as noise, and channels with such residual molecules are characterized as channels with memory. For such channels, the theories of Fick's diffusion and particle location displacement are used to characterize the channel capacity as a function of a collection of parameters, including the diffusion coefficient of the channel, the temperature, the distance between end-transceivers, and the bandwidth of the transmitted signal [166].

#### 2) IoBNT in Public Health Applications

Late 2019 and 2020 have seen the novel coronavirus disease named COVID-19 spread worldwide, causing high fatalities and a plethora of other public health issues. More generally, such outbreaks, including the severe acute respiratory syndrome (SARS) in 2002, the middle east respiratory syndrome (MERS) in 2012, the Ebola virus disease in 2014, and the seasonal influenza, raise questions about the manner in which public health systems should react to such epidemics and pandemics. The widespread havoc caused by pandemics calls for effective means to identify new viruses, understand their mechanisms of viral infection, and devise efficient tools for treatment and vaccination.

In order to facilitate the development of antiviral and preventive solutions, researchers have looked into creating biosensors that can monitor the cleavage of proteases within infected cells [167]. Proteases are generated as a result of the cell being infected by the genome of coronavirus, which is a type of RNA virus. Other byproducts include synthesized polyproteins which can replicate and transcript to generate more RNAs, and structural proteins that can construct new virions [168]. Two types of proteases found in the coronaviruses that cause SARS and MERS (i.e., SARS-Cov and MERS-Cov) are papain-like protease and 3C-like protease. The biosensor, which is based on luciferase, is used to identify potential broad-spectrum coronavirus papain-like or 3C-like protease inhibitors.

The SARS-CoV-2 virions that cause the COVID-19 disease have a diameter of 50–200 nanometers approximately [169], and infect the human respiratory system via human-to-human spread, in the form of droplets discharged when an infected person coughs or sneezes [170]. COVID-19 has thus far posed unprecedented challenges worldwide in testing, treatment, and vaccine development. The IoBNT is envisioned to have immense potential in the molecular diagnosis of emerging viruses of this kind. The nanosensors, which can be firefly luciferase-based or other reporter genes, can be used to examine the reverse transcription polymerase chain reaction in collected samples. Other tests include using bio-nano-sensors to identify antibodies from blood samples to examine if the person is infected.

In terms of treatment, although no antiviral drugs are available for COVID-19 yet, studies on influenza treatment can shed light on how the IoBNT could assist in future solution development. A critical step for treatment is the antiviral intervention, which blocks the intracellular signaling pathways to prevent influenza viruses from replication. A reported solution preventing the virus from replication is to use engineered bacteria (i.e., Escherichia coli) to trap the Ebola virus [171]. In the reported work, the blood of a patient with the Ebola virus infection is transmitted to a microfluidic chamber tube outside the body which contains the engineered bacteria. The scattered bacteria can then achieve protein binding with the Ebola virus using chemical bind force and synthetic protein binding receptors [171].

More importantly, the IoBNT serves a unique role as a holistic solution to not only monitor limited types of cells (e.g., squamous epithelial cells from nasopharyngeal swabs for COVID-19 tests), but also across different tissues and systems. It is found that such coronaviruses can also cause damage to digestive and neurological systems [169], [172]. Hence, a series of connected bio-nano-things consisting of various types of engineered bacteria can operate simultaneously to improve test reliability and treatment efficiency.

#### 3) Artificial Intelligence in IoBNT for Health Applications

In the IoBNT network, different systems demonstrate a wide variation in characteristics, thereby requiring varied analytical approaches. For example, in cardiovascular systems, the speed of molecular transmission is determined by the speed of blood flow and heart rate, among other factors, which may vary per person; whereas in the nervous system, the time required to propagate information-carrying electrochemical stimuli through neurons depends on the connectivity of synapses. In order to estimate the error rate and capacity, the existing diffusion-based MC model normally requires several channel parameters to formulate the model for computation. The generic modeling approach provides initial insights into the behavior of molecular signal transmission, however, recent advances in statistical learning, that utilize artificial intelligence, provide increasingly refined solutions for modeling sophisticated molecular information exchange processes. For example, in [71], a signal detection algorithm based on neural networks has been shown to achieve good performance without prior knowledge of the molecular channel, thus lending support to the use of statistical inference

for characterizing molecular communication channels. Furthermore, a neural network-based nano-receiver design has been proposed in [173] which shows good bit error rate performance under the effect of inter-symbol interference.

#### 4) Open Problems for IoBNT

Currently, IoBNT primarily focuses on studies in the domains of physical layer channel modeling, capacity analysis, modulation and coding schemes, and nano-transceiver design. However, research gaps relating to the following aspects need to be overcome:

- **Experimental Validation:** The theoretical models of molecular communications should be validated under realistic channel environments, which include experimental testing. Traditionally, these experimental tests have posed high requirements on lab equipment and the nurturing process of cells and bacteria. While the procedures for such experiments should be strictly followed and executed, at times the cost for testing can be remarkably high. In such situations, simulations based on realistic assumptions serve as an alternative means, which have been commonly adopted in research. The convergence between analytical and experimental approaches should be a joint effors by researchers across fields in telecommunications, biomedical engineering, and signal processing.
- **Data Storage and Management:** The large data sets obtained from experiments or simulations can have many control variables which require efforts to manage and update. Open databases have become a popular trend for sharing raw data to benefit the entire research community for collaboration, and can be a foreseeable direction for research in the IoBNT.

### C. QUANTUM COMMUNICATIONS

As networks continue to evolve beyond 6G, they are expected to incorporate more spectrum, a larger variety of transceiver front-ends, higher complexity in processed signals, and stricter requirement on reliability, and therefore, it is expected that the computational requirements of wireless systems will also increase [174]. To this end, quantum computing has been widely recognized as a key enabling technology for realizing computationally complex systems [175]. Quantum systems are particularly useful for solving complex optimization problems. For example, in the optimal routing problem with multiple objectives, traditional methods, including the geographic routing algorithm, demonstrate significant complexities to yield optimal solutions, and less complex ones often sacrifice optimality [176]. It has been demonstrated that using quantum computing for such problems can efficiently reduce complexity while achieving optimality [177].

However, such computationally intensive tasks often require several hundreds of thousands or millions of interconnected quantum bits, and therefore cannot be performed on a single quantum chip. The need for interconnecting several chips of this kind has given rise to the concept of quantum communications. Quantum communications is thus indispensable for operating quantum systems at scale [178]. More specifically, quantum communications is defined as the exchange of information that adheres to the laws of quantum mechanics, and offers several key advantages: (i) the capability of large-scale parallel computation, (ii) the ability to transfer data in a tamper-proof manner, and (iii) the potential to encode and transmit a large number of multiple data streams simultaneously.

We begin our discussion of quantum communications by describing the following four postulates or rules that govern the operation of such systems [179]:

- **Postulate 1 - The Quantum Bit:** Within the context of classical communications, a binary value of either 0 or 1 per bit is used to represent data. On the other hand, in quantum communications, the quantum bit, or qubit, contains the superposition of both logical values at the same time, of the form
$$\Phi = a_0 0 + a_1 1, \tag{1}$$
where $\Phi$ represents a two-dimensional vector, with the coefficients $a_0$ and $a_1$ being complex numbers, and 0 and 1 being the two logical values.
- **Postulate 2 - The Quantum Register:** Just like computing registers that are used to store multiple bits, quantum registers are used for storing qubits. However, unlike classical registers that are deterministic, the output of a quantum register is probabilistic, i.e., when reading or measuring the quantum register, a different value may be returned each time, thus presenting a major challenge in the implementation of quantum information exchange systems.
- **Postulate 3 - Exponential Speed-up:** Exponential speed-up is a key property of quantum information processing systems. We know that classical systems employ parallelization wherein multiple computing units process parallel streams of data simultaneously. On the other hand, in quantum systems, the entire input information is placed in a single quantum register, and a single quantum computing unit can process multiple register states simultaneously, thus achieving a significant reduction in the time required for computation.
- **Postulate 4 - The Q/C Conversion:** Since it is far easier to perceive information in terms of 0s and 1s, i.e., classical information, it becomes imperative to interpret the results of any quantum operation in the classical domain. To this end, the classical interpretation of (1) implies that, if we were to measure such a qubit, we would receive value 0 with probability $p_0 = |a_0|^2$ and value 1 with $p_1 = |a_1|^2$.

Closely related to the four postulates is the concept of entanglement [179]. Entanglement is a phenomenon in which the quantum states of two or more particles are described with reference to each other. Within this context, these particles exist in a shared state, and are referred to as entangled

pairs. Any action on a particle within the entangled pair immediately affects all other particles within that pair, irrespective of the physical separation between them. For example, if a photon traveling through an optical fiber is entangled with another photon outside the fiber, the photon inside the fiber will experience the same effects as those experienced by the photon on the outside. In this case, entanglement serves as a source of noise in the quantum channel.

Continuing our discussion of quantum channels, we note that classical information theory does not apply to these channels. Unlike traditional wireless communication channels where the large- and small-scale parameters are deterministic or can be stochastically characterized, the capacity of qubit carrying quantum channels is defined as the rate at which classical or quantum information increases with each use of the quantum channel [180].

Moreover, there exist several different types of capacities for quantum channels, including but not limited to the classical capacity, the quantum capacity, the private capacity, the entanglement assisted capacity, and the zero-error capacity. The classical and quantum capacities are the two most commonly used definitions. In particular, while the classical capacity measures classical information transmission over a noisy quantum channel, the quantum capacity represents the amount of quantum information, i.e., qubits, that can be transmitted through a noisy quantum channel. We refer the interested reader to [180] for additional insight into each of these channel capacity types. In the following, we discuss the different types of channels, data routing, and open problems within the domain of quantum communications.

#### 1) Types of Channels

Within the broader domain of quantum communications, we take into consideration the following types of channel, the dephasing channel and the depolarizing channel [181], [182].

- **The Dephasing Channel:** The dephasing channel, also known as the phase damping or phase flip channel, applies a bit flip in the conjugate basis. The impact of the dephasing channel can be best described as equivalent to measuring the qubit in the computational basis and then forgetting the result of the measurement. A more detailed treatment of the nuances of the dephasing channel can be found in [181, §4].
- **The Depolarizing Channel:** The depolarizing channel is often referred to the "worst-case scenario" and describes the fact that the qubit may be left unchanged with a probability $1-p$, with $p \in [0,1]$, or that an error may occur with probability $p$. In this case, the error could be one of three types, with each being equally likely– the bit flip error, the phase flip error, or both. In the event of an error, it is assumed that the channel replaces the lost qubit with a maximally mixed state [182, §2], i.e, all states become equally likely. For example, the maximally mixed state with reference to (1) implies that $a_0 = a_1$.

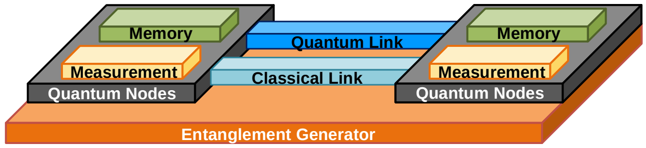



FIGURE 15. Physical entities associated with quantum networks [178].

#### 2) Quantum Communications Networks

Quantum networks are key to the success of distributed quantum computing, and in turn rely on the ability to share quantum states between different quantum devices. However, unlike conventional networks that are based on the store-and-forward paradigm, quantum networks must adhere to the no-cloning theorem which prohibits making copies of an arbitrary quantum state [183]. In order to overcome this restriction, quantum networks rely on the concept of entanglement [184] described earlier, along with quantum teleportation. The process of quantum teleportation [185] leverages entanglement to transmit unknown quantum states between remote quantum devices, through remote entanglement distribution [186].

Further, as shown in Fig. 15, we note the following physical entities that constitute quantum networks [178]:

- **Quantum Nodes:** These are the quantum devices that are interconnected to each other.
- **Communication Links:** These include both classical as well quantum links that interconnect the quantum nodes in the network.
- **Entanglement Generator:** This device is responsible for generating the entangled pairs that are distributed between the quantum nodes.
- **Quantum Memories:** These are primarily used for storing quantum states for the purpose of communication.
- **Quantum Measurement Devices:** Their primary function is the assessment of the generated entangled states.

While the aforementioned entities play a vital role in enabling quantum networks, the process of quantum teleportation is affected by the exponential decay of communication rate with distance, which in turn is offset by the use of quantum repeaters. The routing problem then involves the selection of the optimal path from the source to the destination traversing one or more quantum repeaters resulting in a high-quality entanglement distribution. Further, the routing framework must also take cognizance of the fact that the physical mechanisms underlying quantum entanglement are stochastic, and that the passage of time leads to loss of entanglement between the entangled pair [186]. Expanding upon this, in the following section, we delve into some of the major challenges faced by quantum networks today.

#### 3) Open Problems and Major Challenges

Given the vast differences between the classical and quantum domains there are several fundamental research challenges,

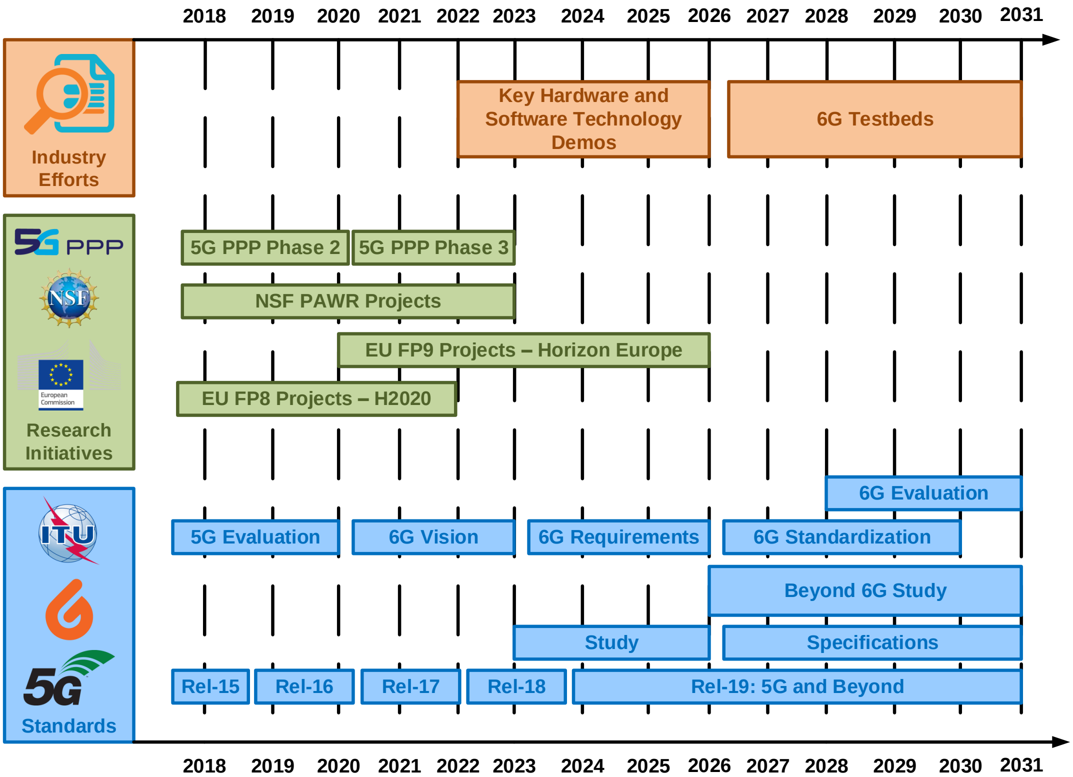



**FIGURE 16.** Projected timeline for 6G and beyond systems.

that are vital to the success of quantum networks as detailed next.

- **Quantum Error Correction:** There are three major challenges faced by error correction techniques for qubits [187]. First, while classical error correction codes assume that data can be duplicated freely, the no-cloning theorem precludes the arbitrary duplication of quantum states. Second, since qubits are susceptible to both bit-flip and phase-flip errors, quantum error correction techniques need to be able to detect both error types simultaneously, unlike classical techniques that take only bit-flips into consideration. Third, there exists the possibility of wavefunction collapse [188] due to measurements on the qubits performed as part of the error correction procedure.
- **Entanglement Distribution:** Long distance entanglement distribution is a key challenge in the realization of quantum networks, impacting the physical, link, and network layers [184]. More specifically, at the physical layer, there is a need for quantum error correction techniques, while the no-cloning theorem necessitates a re-design of the link layer. At the network layer, novel quantum routing metrics are required to ensure optimal path selection.
- **Deployment Challenges:** Quantum computing devices require highly specialized data centers equipped with ultra-high vacuum systems and ultra-low temperature cryostats. Further, while quantum teleportation has been proposed as a means to realize quantum networks, it requires the integration of classical and quantum communication resources, which is a fairly complex problem in itself.

## XII. TENTATIVE TIMELINE FOR 6G

Thus far, we have described the manner in which the evolution of societal needs will guide the transition from 5G to 6G, along with a plethora of new and upcoming use cases that will be best served by 6G. We have also discussed the tentative KPIs associated with 6G and the key enabling technologies that will play a vital role in achieving these next-generation KPIs. As shown in Fig. 16, the increasing technological readiness and worldwide deployments of 5G systems have set the stage for a thoughtful discussion on the future of wireless communications.

While 3GPP standards over the next few years, up to and including Release 18 in 2024, are expected to primarily deal with 5G, the ITU has recently convened the Focus Group on Technologies for Network 2030 (FG NET-2030) [189], to study the capabilities of networks for the year 2030 and beyond. More generally, as we have seen in the preceding sections, each of the presented key technologies has witnessed significant traction in terms of research and development, laying the groundwork for the next generation of wireless communications. Both the National Science Foundation

(NSF) through its Platforms for Advanced Wireless Research (PAWR) initiative [190] and the European Commission [191] are expected to play a major role in the development of 6G.

At the same time, going beyond academia, we expect a significant rise in industry involvement in the development of these technologies over the next few years, culminating in key hardware and software technology demos by 2025, followed by full-scale 6G testbeds in 2026 and beyond. We envision that these testbeds will serve as the perfect backdrop for showcasing the potential of 6G and demonstrating its suitability for use cases such as multi-sensory holographic teleportation, real-time remote healthcare, industrial automation, and smart infrastructure and environments, to name a few.

## XIII. CONCLUSION

This paper surveys the key enabling techniques for the next generation of wireless communication networks, outlines their essential use cases, and provides a perspective on current as well as future research and development efforts. We envision that 6G wireless systems will be largely driven by a focus on wireless ubiquity, i.e., the unrestricted availability of high quality wireless access. To this end, we have highlighted the key enabling technologies that are vital to the success of 6G. By detailing both the operational nuances and open challenges associated with each, we not only hope to provide a detailed insight into the next frontier in wireless communications, but also encourage readers to play their part in the realization of the envisioned ubiquitous wireless future.

## ACKNOWLEDGMENT

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IAN F. AKYILDIZ (M'86–SM'89–F'96) is currently the Ken Byers Chair Professor in Telecommunications with the School of Electrical and Computer Engineering, Director of the Broadband Wireless Networking Laboratory, and Chair of the Telecommunication Group at Georgia Institute of Technology, Atlanta, USA. His current research interests are in 5G and beyond wireless systems, the Internet of Space Things, nanonetworks, Terahertz band communications, and wireless sensor networks in challenged environments. He is an IEEE Fellow (1996) and an ACM Fellow (1997). He has received numerous awards from the IEEE and the ACM, and many other organizations. His h-index is 122, and the total number of citations is above 117K as per Google Scholar as of May 2020.

AHAN KAK received the B.S. degree in Electrical Engineering from V.J.T.I., University of Mumbai in 2016. Currently, he is working toward the Ph.D. degree in Electrical and Computer Engineering under the supervision of Prof. Ian F. Akyildiz. His research interests include software-defined networking, network function virtualization, Internet of things, and cellular and space communications.

SHUAI NIE received the B.S. degree in Telecommunications Engineering from Xidian University in 2012, and the M.S. degree in Electrical Engineering from New York University in 2014. Currently, she is working toward the Ph.D. degree in electrical and computer engineering at the Georgia Institute of Technology under the supervision of Prof. Ian F. Akyildiz. Her research interests include physical layer modeling and wireless system design in millimeter wave and terahertz band communications for 5G and beyond.

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Ian F. Akyildiz (M'86-SM'89-F'96) is currently the Ken Byers Chair Professor in Telecommunications with the School of Electrical and Computer Engineering, Director of the Broadband Wireless Networking Laboratory, and Chair of the Telecommunication Group at Georgia Institute of Technology, Atlanta, USA. His current research interests are in 5G and beyond wireless systems, the Internet of Space Things, nanonetworks, Terahertz band communications, and wireless sensor networks in challenged environments. He is an IEEE Fellow (1996) and an ACM Fellow (1997). He has received numerous awards from the IEEE and the ACM, and many other organizations. His h-index is 122, and the total number of citations is above 117K as per Google Scholar as of May 2020.

Ahan Kak received the B.S. degree in Electrical Engineering from V.J.T.I., University of Mumbai in 2016. Currently, he is working toward the Ph.D. degree in Electrical and Computer Engineering under the supervision of Prof. Ian F. Akyildiz. His research interests include software-defined networking, network function virtualization, Internet of things, and cellular and space communications.

Shuai Nie received the B.S. degree in Telecommunications Engineering from Xidian University in 2012, and the M.S. degree in Electrical Engineering from New York University in 2014. Currently, she is working toward the Ph.D. degree in electrical and computer engineering at the Georgia Institute of Technology under the supervision of Prof. Ian F. Akyildiz. Her research interests include physical layer modeling and wireless system design in millimeter wave and terahertz band communications for 5G and beyond.